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RADIATION AND CONTAMINATION CONTROL

VOLUME THREE
TECHNICAL INFORMATION RELATING TO NUCLEAR WEAPONS EFFECTS

BUREAU OF SHIPS NAVY DEPARTMENT WASHINGTON 25, D. C.

PRINCIPLES OF RADIATION AND CONTAMINATION CONTROL

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We have received so much help from many persons working in many places throughout the years we have been compiling this book, that it would take another book to list them. To every one of them, our sincerest thanks.

To any of them whose words we have paraphrased or whose statistics we have lifted without specific acknowledgement - our apologies along with our thanks.

PRINCIPLES OF RADIATION AND CONTAMINATION CONTROL

(PORACC)

This series of three volumes on the control of radiation and radioactive contamination originated in a field manual developed for the naval participants in nuclear weapons tests at the Pacific Proving Grounds. Thinking that it might be more widely useful, it has been revised somewhat and divided according to "need to know" of the potential readers. The subject matter is presented more completely as the reader progresses from one volume to the next. The scientific foundation, i.e., the nuclear physics and radiobiology, are developed only to the extent needed in facing the practical problems.

The scope of the three volumes is limited to the control of radiation and contamination relating to nuclear weapons effects, and it is applicable primarily to non-wartime situations, although some of the material would be applicable to wartime use. For guidance under tactical situations the reader is referred to such publications as Bureau of Ships Technical Manual, Chapter 90 Radiological Recovery of Ships after Nuclear Weapons Explosions, and NAVDOCKS TP-PL-13 Radiological Recovery of Fixed Military Installations. Criteria and procedures for controlling radiation and contamination relating to nuclear powered ships are not contained in this manual but are contained in NAVSHIPS 389-0153 Radiological Controls for Naval Nuclear Propulsion Plants (Classified).

Volume I is for persons working where there is radiation or using radioactive materials. It contains a general introduction to the physics of radiation and the biological effects that make it dangerous to health, together with techniques for measuring radiation and minimizing the chances that it will injure anyone. It should by itself meet the essential requirements of many persons.

Volume II is for those with special responsibility in regard to radiation relating to nuclear weapons effects. It develops in more detail the fundamentals given in Volume I.

Volume III contains data needed to conduct training courses for which Volume II might serve as a textbook. It should be referred to when what is given in Volume I or even in Volume II seems insufficient.

VOLUME III

TECHNICAL INFORMATION

Preface

This volume was prepared primarily to supplement the basic radiological data presented in Volumes I and II, and to provide instructors with more detailed information of the biological effects of radiation, radiation phenomenology, radiation instruments, and health physics data. Secondarily, it provides the industrious student and radiological safety personnel with additional reference material. Although some of the information may be found in other texts, such as The Effects of Nuclear Weapons, and in other references as listed on page 79, Volume III was prepared to provide sufficient data to teach radiological safety from one series of texts, The Principles of Radiation and Contamination Control (PORACC). A reader with one or two years college training should easily understand the material in this document.

VOLUME III

TECHNICAL INFORMATION

Contents

APPENDIX A

Formulae, Graphs, and Tables for Health Physics Computations

APPENDIX B

CHAPTER 1

BIOLOGICAL EFFECTS OF RADIATION

IONIZING RADIATIONS are capable of causing harmful effects on living organisms. Since the discovery of X rays and other ionizing radiations, there has been much study to determine the cause and mechanism of the biological effects from ionizing radiations. Although early workers with X rays and radium provided the first human examples of biological change and damage, most of the constructive investigation has been carried out in the past decade.

The effect of large doses of radiation is fairly well known. However, the amount of radiation required to produce certain lesser effects, the actual mechanism of damage and change, and the extent of damage in the event of low doses of radiation are uncertain in many cases. Continuous effort is being made to increase the knowledge of the biological effects of radiation at all exposure levels and in all areas of possible biological damage.

UNITS OF RADIATION MEASUREMENT

A. Roentgen (r). The roentgen is the unit of exposure dose for X and gamma radiation up to 3 Mev in energy. One roentgen is an exposure dose of X or gamma radiation such that the associated corpuscular emission per 0.001293 gram of air produces, in air, ions carrying 1 electrostatic unit of quantity of electricity of either sign. At standard temperature and pressure, 0.001293 grams of air occupies a volume of one cubic centimeter. Restated, the roentgen is a unit of dose for X and gamma radiation only (below 3 Mev) and expresses the absorption of energy in air equivalent to the liberation of one esu of charge per cubic centimeter of air under standard conditions. Likewise, one roentgen produces an energy absorption of 87 ergs per gram of air (NBS-62*) which is, in turn, equivalent to an energy absorption of 93 ergs per gram of mammalian tissue.

B. Rad. The rad is the unit of absorbed dose. It is defined as the transfer of 100 ergs of radiant energy per gram of material (tissue, etc.) at the point of interest. The rad applies to all types of radiation.

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* Report of the International Commission on Radiological Units and Measurements (ICRU), 1956. April 10, 1957.

C. Rep. The rep, roentgen-equivalent-physical (defined in the Glossary), is an obsolete unit which has been replaced by the rad.

D. Rem. The rem, rad-equivalent-man, is the dose of radiation that produces the same biological effect, in the particular circumstances, that would be produced by 1 rad of X radiation. The rem applies to all types of radiation. The dose in rems is equal to the dose in rads multiplied by the RBE for the corresponding biological effect.

RELATIVE BIOLOGICAL EFFECTIVENESS (RBE)

Various radiations absorbed in a specific organ and delivering equal amounts of energy (ergs/gm) will result in different biological effects to that organ. While it has been observed that the various ionizing radiations produce qualitative effects which are indistinguishable from each other, these different radiations are not quantitatively equivalent. That is, the biological effects appear to be the same but the magnitude of the effect varies with the type of radiation, even though the energy delivered to the tissue in question is the same.

We think that the difference in biologic effect is due to the difference in density of ionization where the radiation is absorbed. Gamma rays and X rays give up their energy by producing high speed electrons just like beta rays. These produce only about 5 ion pairs per micron as they go through the cells,that is, until they have slowed down and have only a few hundred ions yet to make. But neutrons give up their energy to atomic nuclei, which are 1800 times as heavy as electrons and do not move nearly so fast for the same energy. So they make a couple of thousand pairs of ions per micron all along their path. But some biological (cytologic) effects have been found on which the crowded ions seem to be wasted and the RBE, surprisingly, is less than 1, although for most biological effects the increased ion density increases the RBE. The concept of relative biological effectiveness (RBE) quantitatively compares the effects of the various types of ionizing radiations. RBE is defined as the ratio between gamma- or X-radiation dose and the dose of the radiation in question that is required to produce the same biological effect. Assuming an r of gamma radiation as unity, the degrees of relative biological effectiveness are listed in Table 1.1.

INTENSITY: DOSE AND DOSE RATE

The Report of the International Commission on Radiological Units and Measurements (ICRU) 1956, National Bureau of Standards Handbook 62, April 10, 1957, recommends that the roentgen be used as the unit of exposure dose for X and gamma radiation. The exposure dose of X and gamma radiation at a certain place is a measure of the radiation that is based upon its ability to produce ionization. ICRU also

TABLE 1. 1

RBE Values for Various Ionizing Radiations

Type of [1] Radiation	RBE	Based on	
		Radiation Condition	Biological Effect
X or gamma	1	Whole body	$LD\text{-}50_{30}$ [2]
Fast Neutrons (>0.1 Mev)	1.7	Whole body	$LD\text{-}50_{30}$
1 Mev neutrons	10-30	Lens of eye	Cataract formation
	1-5	Whole body	Genetic effect
Thermal neutrons	1-3	Whole body	Systemic effects [3]
Beta	1 [4]	Body organ [5]	Systemic effects
Protons	5-10	Body organ	Systemic effects
Alpha	10	Body organ	Systemic effects
Recoil atoms	20	Body organ	Systemic effects

(1) The penetrating ability of the radiation and the location of the emitter will determine which organs will be affected. (See page 13 ff.)

(2) $LD\text{-}50_{30}$, (Lethal dose, 50), radiation dose that will cause death to 50% of the population within 30 days.

(3) Systemic effect is a generalized body effect pertaining to or affecting the body as a whole.

(4) A value of 1.7 is used if max energy $E_m \leqq 0.03$ Mev.

(5) External beta rays (effect on skin) have such a high absorption coefficient that the absorbed dose changes significantly over fractions of a millimeter in depth. Differences in effectiveness are attributable to the distribution, not to the RBE.

recommends that the rad be used as the unit of absorbed dose for all types of radiation. The absorbed dose of any ionizing radiation is the energy imparted to matter by ionizing particles per unit mass of irradiated material at the place of interest. Thus the exposure dose is a measure of the radiation field while the absorbed dose is a measure of the energy imparted to matter by the radiation field.

The term "intensity of radiation" is used to signify the radiation flux density, i.e., the amount of radiation energy passing perpendicularly through a unit surface area in unit time. It is expressed in ergs/cm^2-sec. The quantity of radiation is the time integral of the radiation intensity expressed in ergs/cm^2. It is to be noted that neither the intensity nor quantity of radiation signifies the absorption of radiation energy. They just tell how much radiation energy passes through a surface, nothing about what happens in the volume or mass of material.

The term "dose" as used by PORACC signifies the absorption of any type of radiation energy in any matter. If 100 ergs of any type of radiation energy is absorbed in any type of matter, the unit is the rad. If 87 ergs of X- or gamma-radiation energy is absorbed in 1 gram of air, the unit is the roentgen (r). One roentgen is equivalent to the absorption of 87 ergs per gram of air or equivalent to the absorption of 93 ergs per gram of tissue. For practical purposes, the roentgen and the rad will be considered equivalent for measuring X or gamma radiation. The use of the roentgen unit signifies X- or gamma-radiation energy absorbed in air. The use of the rad unit requires a definition of the type of radiation and the material in which it is measured.

The term "RBE dose" is used to signify the human biological dose, i.e., the radiation energy absorbed in man. The unit of RBE dose is the rem. The dose in rems is equal to the dose in rads multiplied by the RBE of the radiation in question. Table 1.2 summarizes these concepts.

IONIZATION IN TISSUE

Radiation injury to tissue varies in relation to the energy of the radiation, the absorbed dose, the time span over which the dose was received, the amount of body area irradiated, plus other factors not so well defined. Ionization of the atoms which make up the chemical constituents of the tissue cells, as the result of interactions with the incident radiation, is probably the basic cause of injury.

The cell is the basic unit of all tissue. It contains proteins, sugars, lipids, and minerals in an aqueous medium. When a cell is irradiated, ionization causes disruption of the chemical bonds which hold the cellular organic compounds together, and abnormal chemical changes result. These chemical events occurring within the cell can result in

TABLE 1.2

Units of Radiation Measurement

Term	Unit	Phenomena
Intensity	ergs/ cm^2 - sec	Rate of radiation energy passing through unit surface area.
Dose	1 rad = 100 ergs/gm	Amount of any radiation energy absorbed per gram of any material.
	1 r = 87 ergs/gm of air	Amount of X- or gamma - radiation energy absorbed per gram of air.
Dose Rate	1 rad/hr = 100 ergs/gm/hr	Rate of any radiation energy absorption per gram of any material.
	1 r/hr = 87 ergs/gm of air/hr	Rate of X- or gamma - radiation energy absorption per gram of air.
RBE Dose	rem = (RBE) x rad	Biological dose.
RBE Dose Rate	rem/hr = (RBE) x rad/hr	Biological dose rate.

death of the cell; complete destruction of the cell's ability to reproduce; partial, incomplete, or faulty function (as of glandular cells); production of genetic mutations; and other changes.

The parts of the cell most sensitive to radiation are the chromosomes contained in the cell nucleus. These are the carriers of the body's hereditary characteristics. Radiation can cause changes in the chromosome material or reproductive cells which may result in altered hereditary characteristics in future offspring.

RADIOSENSITIVITY OF TISSUE

In observing the effects of radiation upon body tissue, we note that various types of tissue respond quite differently to a given kind and dose of radiation. This difference in tissue response is known as radiosensitivity.

As yet, it is not completely understood why some tissues are more readily affected by radiation than others. Several generalizations substantiated by experimental observations permit the prediction of the degree of radiosensitivity of a particular type of cell or tissue. More rapidly growing and active cells tend to be more radiosensitive. Tissue and cells which are less specialized or less differentiated tend to be more vulnerable to radiation. In general the nucleus of a cell is more radiosensitive than the cytoplasm; thus, a large cell with much cytoplasm is less affected than one with a proportionately larger nucleus. On the basis of these generalizations, the following may be accepted as a list of common cells and/or tissues in the order of decreasing radiosensitivity:

A. Lymph tissue, particularly lymphocytes (cells of the body fluid).
B. White blood cells and immature red blood cells found in bone marrow.
C. Cells lining the gastro-intestinal canal.
D. Cells of the reproductive organs.
E. Skin, particularly the proliferating portion.
F. Blood vessels and body cavity lining.
G. Tissues of the liver and adrenal glands.
H. Other tissues, including bone, muscle, and nerves, in that order.

Advances in the use of radiation in medicine have come about largely by adapting the techniques of treatment in order to take advantage of the different sensitivities of various tissues. The high vulnerability of cancer tissue to radiation damage is an example of this principle. Localized malignant cancer may be irradiated and destroyed without excessive damage to the normal tissue in which it is embedded.

TIME FACTOR VS TOTAL DOSE

The biological effect of radiation depends not only on the total amount absorbed (dose) but also on the rate of absorption (dose rate). In most instances, the biological effect of a given dose decreases as the dose rate decreases. For example, 600 r would probably be fatal to a man if it were absorbed by the whole body within a period of a day but would probably have no noticeable effect if absorbed evenly over 30 years because the body tissue is able to recover when the dose rate is low. If the dose rate is increased, a point is reached where recovery can no longer keep up with damage, and permanent biological damage may result. "Recovery" or "reversibility" is associated with the normal ability of most tissues to recover from damaging stimuli. A large dose received fairly promptly is usually referred to as an acute dose, while protracted exposure is usually referred to as chronic dose.

The term "dose" as used in radiobiology usually means absorbed dose, i.e., the energy absorbed per gram. There is a quantitative relationship between the extent of damage and the dose. A plot of dose vs effect for various tissues shows two forms of response relationship which may be observed. These are shown in Fig. 1.1. Curve A represents a "non-threshold" case where some effect is produced at any radiation dose greater than zero. This relationship may or may not be a linear one, although induction of gene mutations by radiation is probably a good example of a linear non-threshold response. Curve B illustrates the "threshold" case. Here the effect is not measurable until a certain minimum or threshold dose is exceeded. The majority of acute radiation effects are thought to be of this type. It may be that as more delicate means are found to measure biological effects, more effects will be found to be of the "non-threshold" type.

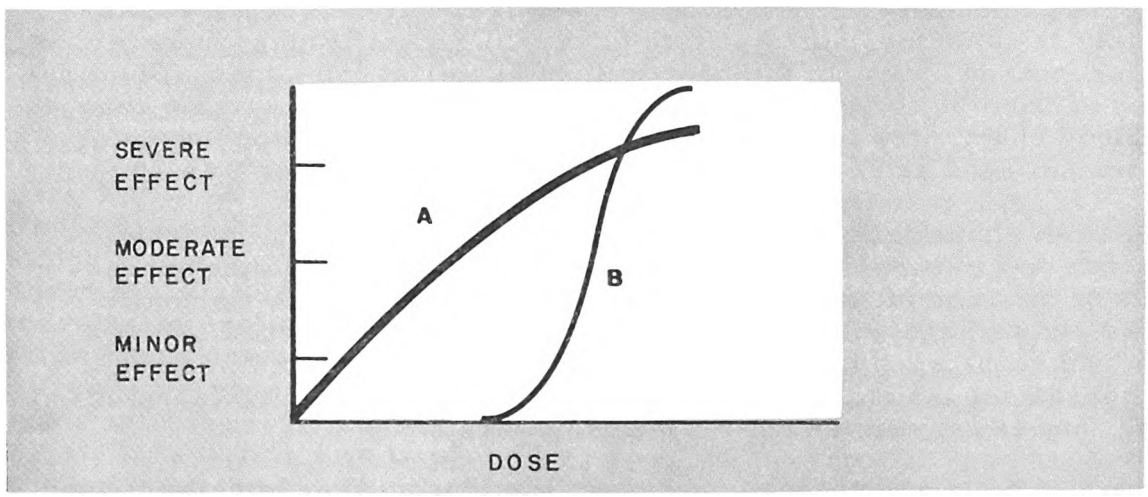


FIG. 1.1 THRESHOLD AND NON-THRESHOLD DOSE RESPONSE

Effects of radiation manifest themselves at different times after exposure. Those which appear within approximately a month are termed acute effects. This includes the immediate (0 to 48 hours), and the delayed (one to five weeks) effects. Chronic effects would include those which result in persistent changes (radiation dermatitis, vascular or atrophic changes) and long term effects (appearing after one year--tumor induction, cataract formation).

Recent animal experiments indicate that the acute effects produced by radiation exposures in excess of 100 r are dependent on the total dose and the time span over which the dose is received. Most chronic effects are independent of the time span over which the dose is received and depend only on the total dose received.

ACUTE RADIATION EFFECTS

The penetrating component injures the inner organs. The sensitivity of the organs varies considerably. Blood-forming tissues are very sensitive, as is the lining of the intestinal tract. Severe injury of blood-forming tissue can produce death in man between 1 and 10 weeks as a result of the destruction of the cells which make red and white blood cells and platelets.

One of the first symptoms of an overexposure to penetrating radiations is a change in both red and white blood cell counts. Normally, the red blood cell count is $4\frac{1}{2}$ to 5 million per cubic mm and the white blood cell count varies from 5,000 to 10,000 per cubic mm. After a variable initial rise the white cell count drops, reaching a minimum level in about seven days. If the white cell count falls below 500 cells per cubic mm of blood, the condition is almost certain to be fatal; a count of 2,000 cells places the dose in the critical range. Since a number of diseases and conditions also influence the white cell count, this is not a completely reliable index of radiation injury. Of significance, however, is the decreased ability of the body to fight bacterial infections. Since a dose of from 20 to 50 rem is required to produce a measurable change in blood count, this is considered a threshold effect. Blood counting is seldom used as an indication of exposure to doses less than 20 rem.

Radiation also alters the production of red blood cells in the bone marrow and results in anemia. Since there is a delay in the appearance of the anemia, it is a "late" sign of overexposure. Normally, blood clots whenever it reaches damaged tissue. Exposure of a few hundred roentgens modifies the clotting mechanism, resulting in hemorrhaging which is an important symptom in severe radiation injury, and is sometimes a direct cause of death.

When red cells are not made, anemia develops as the old cells die and disappear from the circulation. Severe anemia can be the cause of

death. When white cells disappear, the body is more sensitive to infections because these cells normally attack invading germs. Infections under these conditions can be controlled only temporarily by modern drugs. Permanent cure depends upon recovery of the blood-forming tissues. The platelets protect the body from excessive bleeding. When these disappear, the body will bleed from wounds or may bleed spontaneously into vital organs. Deaths produced by this effect were observed at Hiroshima and Nagasaki, and also occur in other diseases of man that are familiar to all physicians (bone marrow depression from chemicals such as benzol). Injury to the lining of the gastro-intestinal tract can also cause death in the first two weeks because the intestine loses the ability to retain water and vital salts. Death occurs from the loss of these vital elements. This phase was mistaken for dysentery or cholera by the Japanese physicians who did not know, at that early period, that the bomb produced radiation. However, it takes more radiation to produce this injury than it does to injure the bone marrow and its blood-forming cells. Treatment of this type of injury is very unsatisfactory.

Much higher doses of radiation can injure the brain and produce very early deaths. There is no treatment for this. Even if one survived the brain injury, one has yet to face the intestinal injury and later the effects of bone marrow injury.

Blood can be replaced and infection can be controlled for a limited period of time to give the body a chance to regenerate its own tissues. Man has not yet learned how to stimulate satisfactorily the regeneration of blood-forming tissues, nor has he learned how to transplant blood-forming tissues from one individual to another. Although much has been accomplished, the means of curing radiation sickness have yet to be realized. Under certain conditions, curing radiation sickness is an accomplished fact in some animals. However, the gap from the laboratory to the clinic, when bridgeable, is often long and roundabout.

Table 1.3 is a tabulation of the acute effects produced by various short-term exposures to penetrating radiation in man. It should be stressed that response to various doses differs between individuals, and many factors affect the comparative degree of tissue injury.

Figure 1.2 presents an estimate of incidence and duration of sickness for populations exposed to various amounts of whole-body penetrating ionizing radiation.* The clinical course of the acute radiation syndrome is also illustrated in Figure 1.2. The initial reactions (prodromal phase) of nausea, malaise, anorexia (loss of appetite) and vomiting develops within 24 hours after exposure. The symptoms of the prodromal phase peak at about 8 hours post exposure and gradually subside until the individual is relatively well around 3 days post exposure. It is during this latent phase, about 3 days to 2 weeks post-exposure, that the exposed individual is again capable of unrestricted activity. At the end of the latent phase, symptoms of the prodromal

* Gerstner, H. B., Military and Civil Defense Aspects of the Acute Radiation Syndrome in Man, Air Force School of Aviation Medicine, Report 58-6, November 1957.

TABLE 1.3

Acute Effects of Whole-Body Penetrating Ionizing Radiations on Human Beings

Dose in less than one week (r)	Effects[1]
0-150	No acute effects other than blood cell changes - may be a serious long-time hazard.
150-250	Nausea and vomiting within 24 hours, minimal incapacitation after 2 days.
250-350	Nausea and vomiting in under 4 hours. Some mortality will occur in 2 - 4 weeks. Symptom-free period 48 hours to 2 weeks.
350-600	Nausea and vomiting likely before 2 hours. Mortality probable in 2 - 4 weeks. Incapacitation prolonged.
Greater than 600	Nausea and vomiting almost immediately. Mortality in 1 - 2 weeks.

(1) For exposures extending over a period of more than a few hours, the temporal relationships will be modified somewhat from those shown. For example, a dose of 250 - 350 r given in 3 days will most certainly not produce nausea in 4 hours.

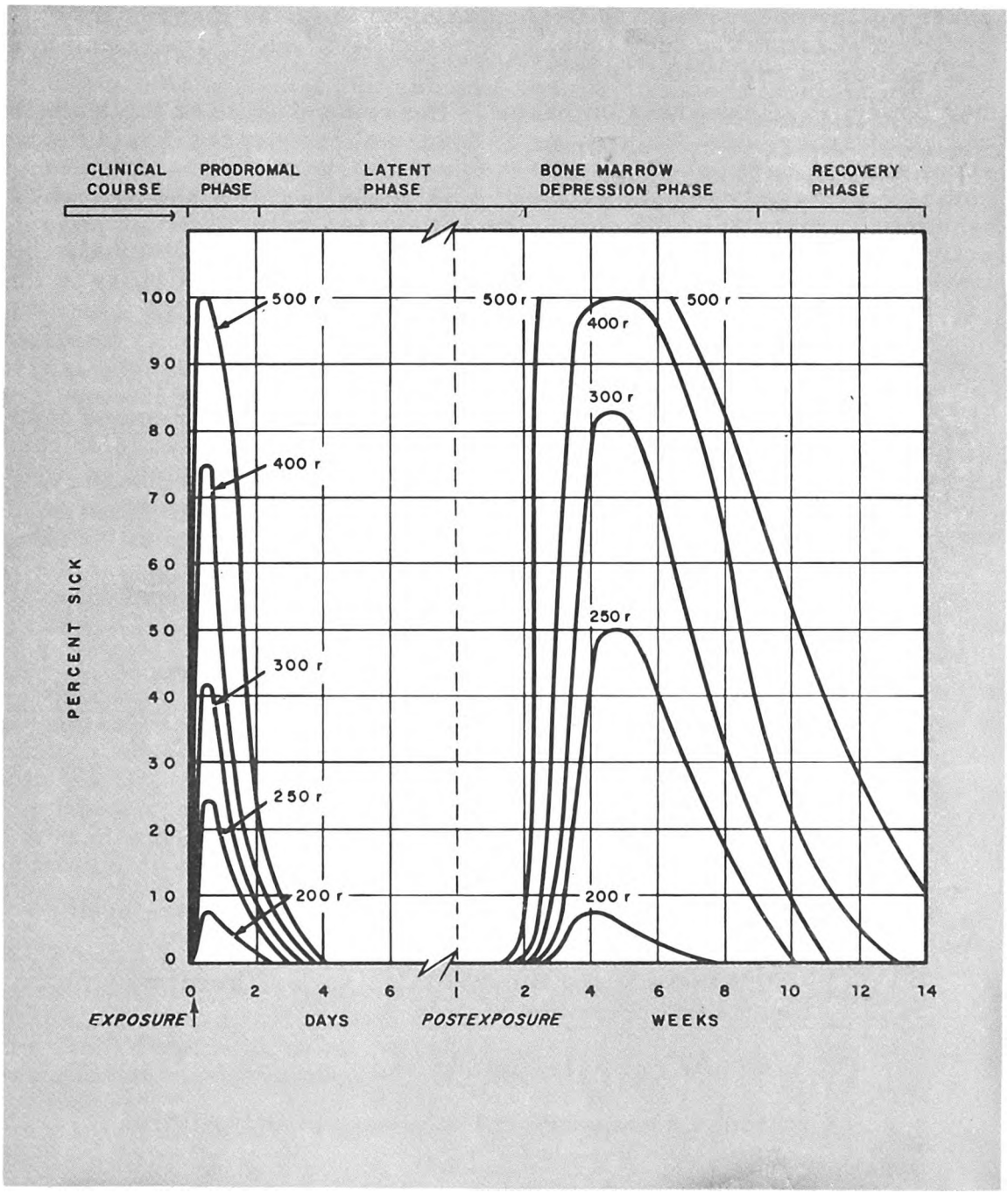


FIG. 1.2 ESTIMATE OF INCIDENCE AND DURATION OF SICKNESS FOR POPULATIONS EXPOSED TO VARIOUS AMOUNTS OF PENETRATING IONIZING RADIATION

phase again appear marking the beginning of the bone marrow depression phase. The individual's body condition deteriorates and hospitalization is required.

The bone marrow depression phase is the critical state of the acute radiation syndrome. This phase of bone marrow depression (aplastic anemia) culminates at about 4 weeks post exposure. Recovery becomes certain between the 40th and 50th day with convalescence beginning at around the 60th day. The patient can return to normal activity at about 3 months post exposure. For a given individual, the time sequence of the syndrome will depend on his susceptibility to ionizing radiation.

CHRONIC RADIATION EFFECTS

Excluding genetic effects (it should be noted that the ovaries and testes are very radiosensitive; however, it is very difficult to establish the genetic effects in man at this time since man has been living in the nuclear age for less than one life span), animal experimentation has demonstrated that the following may happen:

1. Life span may be shortened - the shortening increases with total radiation dose.

2. The incidence of various types of cancer may increase and may occur earlier in life.

3. Degenerative diseases, cataracts, premature aging, etc. can occur.

4. Limited disturbances may be present in the growth of young animals.

In the Japanese survivors, the following developments have been observed:

1. Cataracts of a mild sort that, so far, have not seriously impaired vision.

2. Definite increased incidence of leukemia.

3. Moderate impairment in growth of the children who were exposed.

4. A questionable increased incidence of total bone marrow failure, i.e., aplastic anemia.

5. Alterations in life span. Degenerative diseases are being watched for, but it is too early for a definitive answer.

Since the discovery of radiation, general clinical experience has shown that uncontrolled use of X rays or other radiation sources will increase the incidence of leukemia and aplastic anemia in man. In addition, local injury of the skin may result in skin ulceration and late skin cancers. As a result of ignorance, many of the pioneer physicists, chemists, and radiologists have died from overexposure to radiation received in performing their work. Today we are well informed, and there is no longer any excuse for these tragedies, because prevention is simple.

EXTERNAL EXPOSURE, DEEP VS SURFACE*

External exposure resulting from exposure to an ionizing radiation source outside the body may be divided into two classes--the deep exposure and the surface exposure. The former is concerned with radiation of sufficient penetrating power to reach the blood-forming organs of the body. The latter results from radiations which pass only through the first few millimeters of skin and are classed as soft radiations. Although the variety of conditions of external radiation is unlimited, this discussion will be confined to those resulting in whole body radiation and to those biological effects most likely to occur therefrom.

Deep Exposure is obtained principally from gamma and high-energy neutron radiation. Gamma radiation is characterized by a low specific ionization with high penetrating power. Neutrons are moderately penetrating particles which cause ionization by interactions with atoms making up tissue constituents. The most important of these interactions is that with tissue hydrogen. Collision of the neutron with a hydrogen atom produces a high-energy "recoil proton" which in turn produces tissue ionization.

Surface Exposure is caused by radiations such as alpha and beta which penetrate only a few millimeters of skin, as well as by the penetrating radiations as they pass through the skin. Surface exposure may result either from deposition of radioactive material on skin, or from radioactive substances in the general environs.

The surface effects occur within the primary radiation-sensitive system of the skin--the basal layer of cells. This basal layer is constantly dividing so as to replace the aging epidermal cells. Table 1.4 summarizes surface effects according to the best existing information as to estimated dose required.

From this data, it is possible to construct an operational surface-effects table similar to that formulated for the deep hazard. If severe erythema is accepted as the acute effect which will incapacitate, then

* Alpen, E. L., Radiological Hazard Evaluation - A Critical Review of Present Concepts and a New Approach Thereto, USNRDL-TR-186, 22 October, 1957.

TABLE 1.4

Biological Effects of Radiation on the Skin

Immediate - appearing from 0 - 48 hours after exposure.

1. Erythema (reddening of the skin as in severe sunburn) and itching. Estimated dose required (EDR): 600 - 1000 rads. If 600 rads, will probably appear within 48 hours; if 1000 rads, will probably appear within 24 hours.

2. Vesication (formation of blisters). EDR: between 15,000 and 100,000 rads.

Delayed - appearing from one to five weeks after irradiation.

1. Second wave erythema. EDR: 600 - 1000 rads.

2. Vesication and desquamation (loss of skin). EDR: 2500 rads.

3. Epilation (loss of hair). EDR: 300 - 700 rads.

Persistent Changes

1. Radiation dermatitis. Persistent ulceration in which skin repeatedly breaks down requiring replacement of skin. EDR: More than 1000 rads.

2. Vascular changes. Visible spiderwebbing of surface veins. May contribute to dermatitis. EDR: 500 rads to the blood vessels.

3. Atrophic changes. Skin becomes very thin and easily damaged. EDR: Unknown.

Long Term - appearing after one year.

1. Tumor induction. EDR: 1000 - 2000 rads. A statistically significant increase in tumors has occurred in irradiated animals. Not predictable on an individual basis. Possible genetic effect at the cellular level.

2. Less severe radiation dermatitis. EDR: Unknown.

3. Cataract formation. EDR: 2000 rads to lens.

a dose of 600 rad is set as the upper limit for operation based upon the criteria of maximum acceptable acute effects. The same reasoning holds for the 0-150 r region of whole body penetrating ionizing radiation. For doses over 600 rad, Table 1.5 provides guidelines for accepting or rejecting maximum exposure levels.

Caution should be used when estimating the beta dose rate from a gamma dose rate measurement as is often done in fission product fields. The common factor assumed is that the beta dose rate is ten (10) times the gamma dose rate. This ratio is determined by field measurement where the gamma dose rate from an extended source of distributed fission products arises from as far as several hundred meters from the detector, while a beta dose originates from a radius of only a meter or two from the detector. Thus, in estimating the beta dose when the detector has a limited field of view, such as in monitoring a vehicle, the beta to gamma ratio may no longer be 10 to 1 since the detector is no longer seeing the gamma radiation from several hundred meters but only from 1 - 2 meter radius of the vehicle. The result may be that the beta to gamma ratio is much higher than 10 to 1 and the surface exposure hazard may become a limiting factor.

INTERNAL CONTAMINATION EFFECTS

Radioactive elements taken into the body by ingestion, inhalation or absorption through the skin may be deposited in various organs of the body, thereby constituting a source of internal radiation. The chemical characteristics of the radioactive isotope determine the organ in which it will be deposited, as well as the excretion rate from the body. Radioactive isotopes follow the same metabolic processes as stable isotopes of the same elements. A radioelement, which normally has no stable counterpart in the body, will follow the pattern of another element with similar chemical properties. For example, barium, strontium, and radium normally are not found in the body in large amounts but they all have chemical properties analogous to calcium, and thus will be deposited in bone and otherwise distributed in the body's tissues in a manner similar to calcium.

If a radioisotope has become deposited in the body, the internal exposure is regarded as continuous until the radioisotope is lost by radiological or biological decay. In some cases, this exposure may last a lifetime. Generally, the effects from internal contamination are similar in quality to those resulting from whole body radiation, but since the isotopes are selectively taken up in individual organs, they may cause only localized irradiation. The hazard from a particular radioactive substance depends on the radiosensitivity of the tissue in which it is deposited and also depends on the physical properties of the substance, such as solubility and particle size. These characteristics determine how much of the active material will gain access to and remain in the blood stream and various organs.

TABLE 1.5

Acute Effects of Ionizing Radiation on Skin

Estimated Dose Required (EDR) in 1 week (rad)	Effect[1]
0-600	No acute effects.
600-2000	Moderately early erythema.
2000-4000	Early erythema before 24 hours. Skin breakdown in 2 weeks.
4000-10,000	Severe erythema in 24 hours. Severe skin breakdown in 1 - 2 weeks.
10,000-15,000	Severe erythema in 4 hours. Severe skin breakdown in 1 - 2 weeks.
15,000-100,000	Immediate skin blistering (< 1 day).

(1) For exposures extending over a period of more than a few hours, the temporal relationships will be modified somewhat from those shown. For example, a dose of 4000 - 10,000 rads given in 1 week will not produce severe erythema in 24 hours.

Certain fission products, notably strontium, barium, niobium, iodine, and cesium, are readily absorbed through the digestive tract, and aerosols of these elements are absorbed through the lungs, thus entering the blood stream. Other elements, such as yttrium, zirconium, ruthenium, lanthanum, praesodymium, plutonium, thorium, and uranium are absorbed in slight amounts from the intestinal tract and in somewhat larger amounts through the lungs.

The physiological behavior of an element depends in part on its chemical form. Most fission products are oxides and are usually very insoluble. The large particles of insoluble radioactive compounds circulating in the blood often become lodged in the lungs, liver and spleen tissue.

The "radioactive half-life"(T_R) of an element is defined as the time required for one-half of the element to undergo radioactive decay. In radiobiology there are two other types of "half-life" which are used. They are:

A. "Biological half-life." The time required for one-half of the deposited radioactive material to be excreted from the body.

B. "Effective half-life." The time required for the body to lose one-half of the radioactive material by a combination of excretion and radioactive decay. Effective half-life (T_{EFF}) is related to biological half-life (T_B) and radioactive half-life (T_R) as follows:

$$T_{EFF} = \frac{T_R T_B}{T_R + T_B}$$

The isotopes with long radioactive half-lives are potential hazards if they are taken up by the body .

CHAPTER 2

RADIATION PHENOMENOLOGY

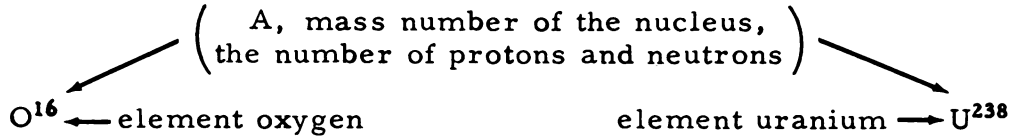
FUNDAMENTAL CONCEPTS OF NUCLEAR PHYSICS

A. Nature of Matter. Matter is anything that possesses mass and occupies space. Matter is made up of molecules and atoms. Molecules are combinations of atoms. An atom is the smallest sub-division of an element which retains the chemical characteristics of that element. It has a central massive core called the nucleus which is made up of non-charged neutrons and positively charged protons. All atoms are made up of various combinations of electrons, protons, and neutrons.

The number of protons in the nucleus of an atom (which is balanced by an equal number of electrons in the electron shells of an electrically neutral atom) is referred to as the Atomic Number of the atom and is represented by the symbol Z. The nuclear charge is always positive. The number of nucleons (protons and neutrons) in the nucleus of the atom is referred to as the Mass Number (A). The number of neutrons in an atom is equal to A-Z. Isotopes are defined as atoms of the same element having the same atomic number but different mass numbers, that is, the same number of protons but a different number of neutrons. The proton-neutron structure of the nucleus is unique for each isotope of an element. All isotopes of the same element have the same chemical properties whether they are radioactive or stable.

B. Nuclear Nomenclature. Every element has a symbol or abbreviation for its name. O is the symbol for oxygen, H for hydrogen, Fe for iron, U for uranium, and so on. Chemical compounds or molecules are represented by identifying their chemical constituents in a symbol formula. H_2O is the chemical formula for water. H_2SO_4 is the chemical formula for sulfuric acid. The subscript to the right of the symbol represents the number of atoms of that element in the molecule. Thus, one molecule of sulfuric acid contains 2 atoms of hydrogen (H_2...), one atom of sulfur (H_2S...), and 4 atoms of oxygen (H_2SO_4). Chemical reactions only involve the rearrangement of the atoms in the molecule and never influence the nuclear structure of an atom.

The symbolic shorthand for identifying the nucleus of an atom is to use the symbol of the element with an upper right superscript to identify the mass number, A. The atomic number Z and element symbol are synonymous.



C. Mass and Energy. It might be expected that the sum of the masses of the constituent particles of the nucleus should just equal the mass of the nucleus. However, it is found that the mass of the nucleus is somewhat less than the mass of its composite particles considered separately. Einstein's principle of the equivalence of mass and energy accounts for this difference. Einstein's principle relates mass (m in grams) and energy (E in ergs) by the equation:

$$E = mc^2$$

where c is the velocity (cm/sec) of light. This decrease in mass, when a number of nucleons combine to form the nucleus of an atom, is converted into energy. This energy represents the binding energy of the nucleus. The binding energy is the energy holding the nucleons together in the nucleus.

Since mass and energy are related, the atomic mass unit (amu), defined as one-sixteenth of the mass of the O^{16} isotope, is used as a standard of mass in nuclear physics.

$$1 \text{ amu} = 1/16 \text{ mass of } O^{16} = 1.66 \times 10^{-24} \text{ grams}$$

$$1 \text{ amu} = 1.49 \times 10^{-3} \text{ erg}$$

An erg of energy is the work done by a dyne of force acting through 1 cm. A dyne is that force which gives to a 1 gm mass an acceleration of 1 cm/sec^2. For example, the weight force exerted by a mosquito is about 1 dyne. Thus, 1 erg of energy is required to lift this insect 1 cm. Another convenient energy unit is the electron volt (ev). One electron volt is the energy acquired by one electron accelerated through a potential difference of one volt. Figs. 2.1 and 2.2 illustrate the electron volt and the erg. The erg and the electron volt are both units of energy or work and are related by the following equation:

$$1 \text{ ev} = 1.60 \times 10^{-12} \text{ erg.}$$

Thus, to raise our mosquito 1 cm requires an expenditure of 1 erg or 6.24×10^{11} ev of energy (Fig. 2.2).

The relationship between the atomic mass unit and electron volt is:

$$1 \text{ amu} = 931.8 \text{ Mev (Million electron volts).}$$

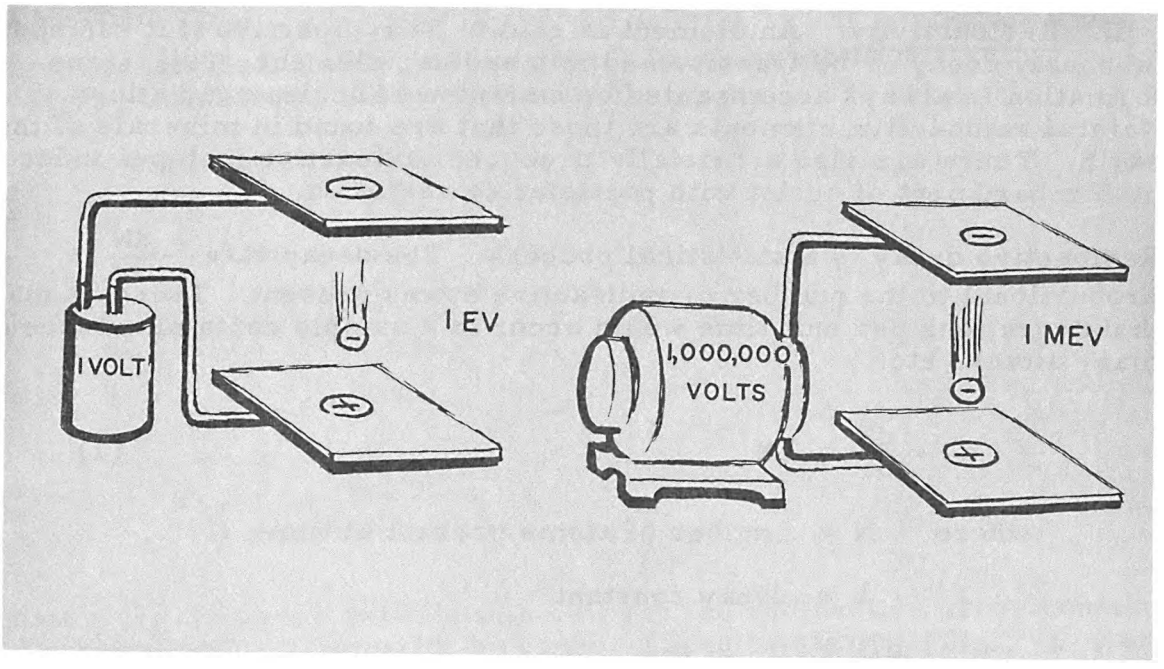


FIG. 2.1 SCHEMATIC ILLUSTRATION OF THE ELECTRON VOLT AND MILLION ELECTRON VOLTS

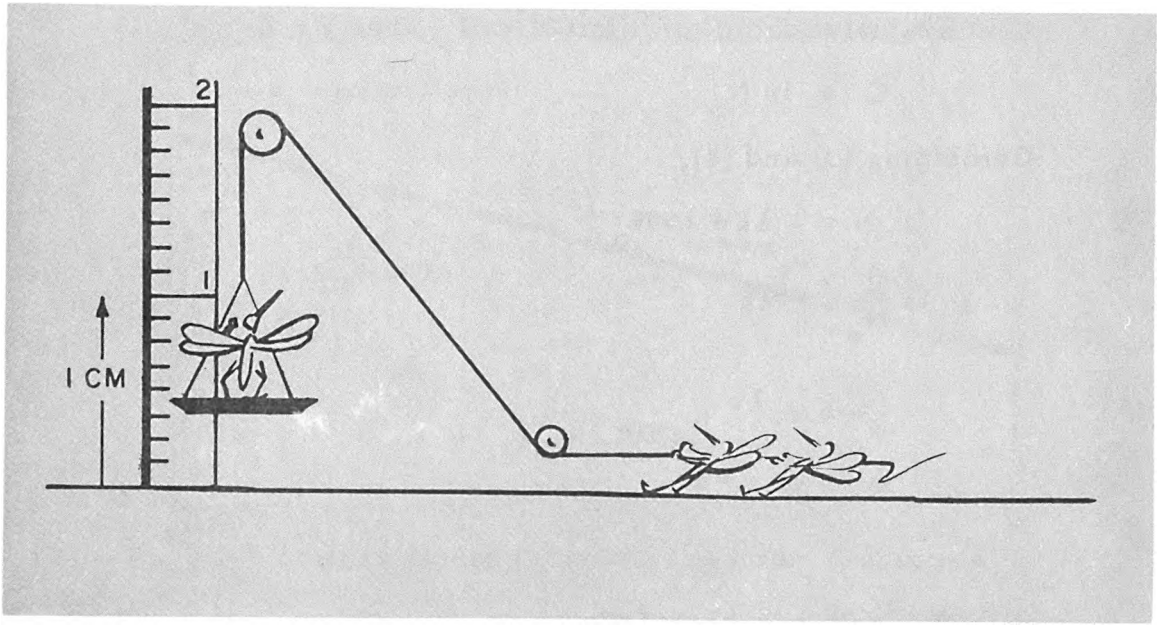


FIG. 2.2 ILLUSTRATION OF WORK EXPENDED (1 ERG) TO LIFT A MOSQUITO 1 CM

D. Radioactivity. An element is said to be radioactive if it can spontaneously decay or be transformed into another element. This transformation is always accompanied by emission of nuclear radiations. Natural radioactive elements are those that are found in minerals of the earth. There are also artificially produced radioactive isotopes induced by bombardment of nuclei with particles or radiation.

Radioactive decay is a statistical process. The decay rate $-\frac{dN}{dt}$ is proportional to the number of radioactive atoms present. Twice as many disintegrations per unit time would occur in a sample containing twice as many atoms, etc.

$$-\frac{dN}{dt} = \lambda N \qquad (1)$$

where N = number of atoms present at time, t

λ = decay constant

$$\frac{dN}{N} = -\lambda\, dt \qquad (2)$$

Upon integration of (2),

$$\ln N = -\lambda t + C \text{ (constant of integration)} \qquad (3)$$

C is evaluated from the limit $N = N_o$ when $t = o$

$$C = \ln N_o \qquad (4)$$

Combining (3) and (4),

$$\ln N = -\lambda t + \ln N_o$$

$$\ln \frac{N}{N_o} = -\lambda t \qquad (5)$$

$$\frac{N}{N_o} = e^{-\lambda t}$$

$$N = N_o\, e^{-\lambda t} \qquad (6)$$

where N = number of atoms present at time t

N_o = number of atoms present at time $t = o$

λ = decay constant

The half-life ($T_{1/2}$) is the time it takes for any given amount of material to decay to one-half its original amount. Thus, at the time $t = T_{1/2}$, $N = N_o/2$. Substituting these values in (5),

$$\ln \frac{\frac{No}{2}}{N_o} = -\lambda T_{1/2}$$

$$\ln 1/2 = -\lambda T_{1/2}$$

$$T_{1/2} = \frac{\ln 2}{\lambda}$$

$$T_{1/2} = \frac{0.693}{\lambda} \qquad (7)$$

Equation (7) shows the relationship between the radioactive decay constant (λ) and the radioactive half-life ($T_{1/2}$). These two terms ($T_{1/2}$, λ) are always used when calculations are made concerning radioactivity and are specific values for each isotope. A semilog radioactive decay plot is illustrated in Fig. 2.3.

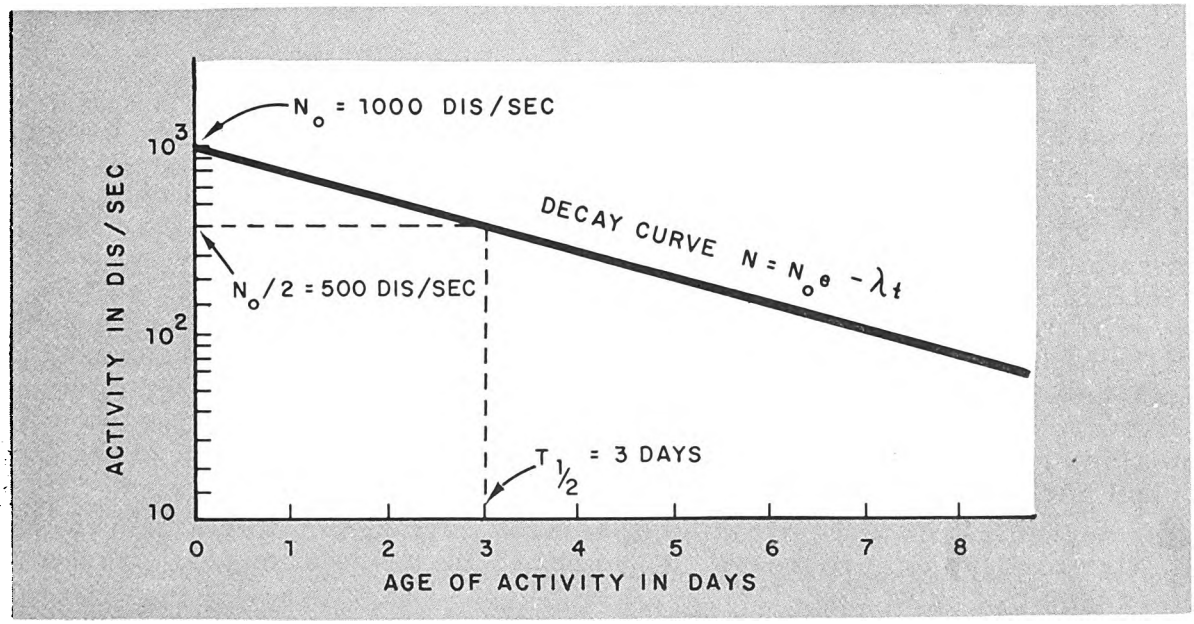


FIG. 2.3 RADIOACTIVE DECAY CURVE

The activity of a given quantity of an isotope is λN where N is the total number of the atoms of the isotope present. Experimentally, the half-life of radium is known to be 1600 years. Its disintegration constant is then:

$$\lambda = \frac{0.693}{T_{1/2}} = \frac{0.693}{(1.60 \times 10^3 \text{ years} \times 3.1 \times 10^7 \text{ sec/year})} = 1.38 \times 10^{-11} \text{ sec}^{-1}.$$

One gram of radium contains 2.6×10^{21} atoms; therefore, the activity of one gram of radium is given by:

$$\text{Activity} = \lambda N = 1.38 \times 10^{-11} \text{ dis/sec} \times 2.6 \times 10^{21} = 3.7 \times 10^{10} \text{ dis/sec.}$$

The activity of one gram of radium, 3.7×10^{10} disintegrations/seconds, is known as the curie and has become the standard unit for measuring the activity of any radioactive substance. A curie is that quantity of radioactive material disintegrating at the rate of 3.7×10^{10} atoms per second.

PROPERTIES OF ELEMENTARY PARTICLES

A. Protons: Charge + 1; Mass: 1.007581 amu (1.6729×10^{-24} gm). The proton is the nucleus of the hydrogen atom and has an electrical charge of + 1. Protons are produced by the ionization of hydrogen gas. Their range, defined as ability to penetrate matter, depends on the energy of the incident proton and the density and atomic number of the absorber. For example, a 10 Mev proton has a range of approximately 1 mm in water.

B. Neutrons: Charge: 0; Mass: 1.008937 amu (1.6751×10^{-24} gm). The neutron is a neutral particle with a mass slightly greater than the proton. Since it has no electrical charge, it is detectable only by means of the products of its interaction with nuclei. Neutrons are produced only as secondary particles in nuclear interactions and always come off as fast neutrons. The neutron diffuses through matter, and interaction with nuclei is the only important flux-reducing mechanism. This nuclear interaction may be (1) elastic or inelastic scattering, (2) radiative capture of the neutron by the nucleus, followed by emission of a photon forming a nucleus having a mass number greater by one than the capturing nucleus, (3) capture followed by emission of a nuclear particle such as a proton or an alpha particle and energy, or (4) capture followed by fission of the compound nucleus.

The mechanics of the penetration of neutrons through matter are very similar to diffusion processes in gases. This penetration is represented schematically in Fig. 2.4.

The neutron travels through the material, changing direction and losing momentum with each collision. The mean free path of the neutron is the average distance between the collisions. This distance is also re-

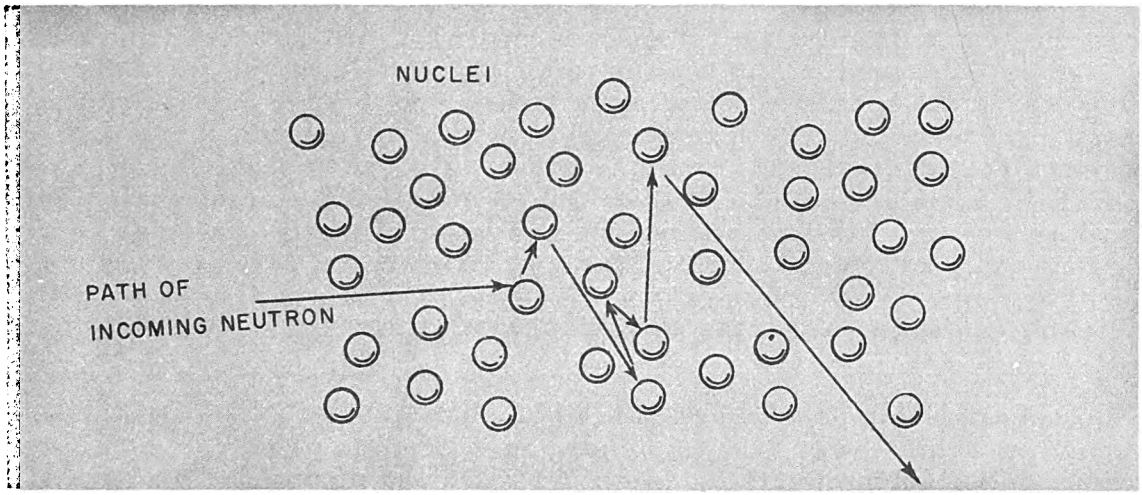


FIG. 2.4 SCHEMATIC ILLUSTRATION OF NEUTRON PENETRATION

lated to the ability of the nuclei to capture or absorb the neutron.

Fast neutrons are neutrons with energies greater than 20,000 ev and are the ones normally produced in a fission reaction. Slow neutrons are produced by moderating or slowing down fast neutrons and have an energy spread from the thermal region, 0.025 ev to 100 ev. Neutrons with energies from 100 ev to 20 kev (thousand electron volts) are referred to as intermediate. It is to be noted that the energy of a thermal neutron is that of a gas molecule flying about at room temperature.

Since the most common mechanism of moderating fast neutrons is through elastic scattering, it follows that nuclei of the same mass as the neutron would be most efficient in slowing down the fast neutron. Billiard balls exhibit this action. If a billiard ball strikes the cushion of the table it will rebound with approximately the same momentum as it had before striking, but if it strikes another billiard ball it loses some of its momentum to the other ball. Thus, the initial ball has transferred or lost some of its energy. Such is the case with hydrogenous material (contains hydrogen atoms of mass 1), such as water, paraffin, or concrete, and its interaction with neutrons. Hydrogenous materials are good neutron shields while materials of high atomic number such as lead or iron are not good neutron shields.

C. Beta Particles (electrons): Charge: - 1; Mass: 5.486×10^{-4} amu (9.11×10^{-28} gm).

Beta particles are emitted by naturally occurring radioisotopes, artificially produced radioisotopes, and fission products. Beta particles are emitted in a continuous energy spectrum with an average energy equal to one-third to one-half the maximum energy. Beta particles, in going through matter, lose energy through the excitation and ionization of atoms (removal of electrons) in the material and by bremsstrahlung radiation (see page 26).

The thickness of beta shielding material (absorbers) is conveniently expressed in units of mass per unit area, mg/cm^2. (Numerical values of mg/cm^2 are obtained by multiplying the thickness in cm by the density in mg/cm^3.) Elements of low atomic number have approximately the same number of electrons (the principle beta absorbing mechanism) per unit volume; therefore, one can take the range of beta particles in aluminum to be a rough measure of their range in any of the lighter elements except hydrogen. In many cases, the energy of the beta particles is such that their range appears to follow an exponential law over a considerable range of absorber thickness. Fig. 2.5 is a graph showing the penetrability of beta particles in various materials.

As the beta particle passes near the nucleus of charge Z, its path will be bent somewhat toward the nucleus. Such bending produces deceleration, and electromagnetic radiation is emitted during the process. This radiation is called bremsstrahlung (German: braking radiation) and represents a loss of energy for the beta particles. The bremsstrahlung process accounts for the continuous spectrum emitted from X-ray tubes. The number of bremsstrahlen produced by the passage of beta particles through matter is proportional to the number of the impinging beta particles and to the square of the atomic number Z of the absorber and the energy of the beta particle. It is therefore preferable to use materials of low atomic number for shielding from beta particles, particularly if the beta particles are of high energy. The electromagnetic radiation due to bremsstrahlung is usually very small as compared to the amount of initial beta radiation eliminated by shielding and needs to be considered only in shielding multicurie beta sources.

D. Alpha Particles: Charge: +2; Mass: 4.00388 amu (6.69×10^{-24} gm). The alpha particle is the helium nucleus He^4. It consists of two protons and two neutrons and, therefore, its mass is large when compared to that of the beta particle. Alpha particles are always emitted with definite discrete energies from a parent nucleus. Because of its relatively large mass and its double charge, the alpha particle has a short range in matter. A 2 Mev alpha particle has a mean range of approximately 1 cm in air, while the average range of a 2 Mev beta particle in air is approximately 300 cm. Alpha particles are completely absorbed by a sheet of paper.

Alpha particles lose energy in an absorber by excitation and ionization of the absorber atoms during the collision process. Interaction with nuclei is not an important flux-reducing mechanism. The alpha particle has high specific ionization properties, producing between 2,500 and 6,000 ion pairs per mm of air. This specific ionization is nearly inversely proportional to the energy of the alpha particle and varies with the distance traveled. Fig. 2.6 shows the mean range of alpha particles in air.

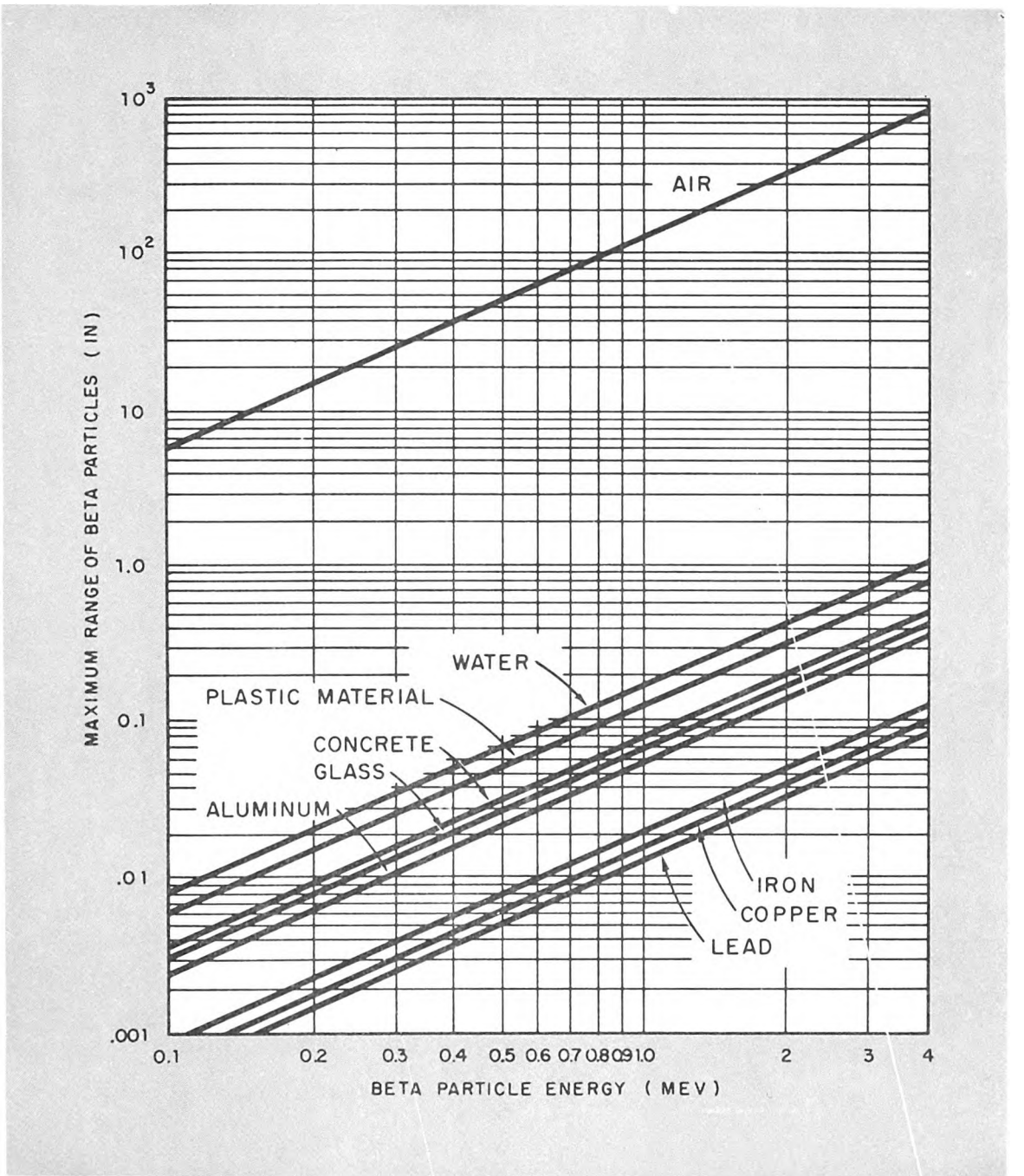


FIG. 2.5 PENETRABILITY OF BETA RADIATION

E. Photons (Gamma and X-ray): Charge: 0; Mass: 0. Gamma rays or photons are electromagnetic radiations which appear during nuclear transitions. (Gamma rays, X rays, light rays, and radio waves are all electromagnetic radiations differing only in wave length and source.) These transitions frequently follow beta and alpha particle emission. X rays are electromagnetic radiation produced by X-ray tubes or Van de Graaff machines either by rearrangements of atomic electrons involving deep lying orbits or by the bremsstrahlung process. There is no difference between X rays and gamma rays of the same energy (except the point of origin). The term photon can mean either.

Photons lose their energy through their interaction with matter. The energy of the photon is transferred to matter principally through three mechanisms: photoelectric effect, Compton effect, and pair production. In the photoelectric effect, the entire energy of an incoming photon is transferred to an atom of the absorber and an electron (now called a photoelectron) is released from the atom of the absorber. This is the predominant absorbing process for photons of low energy (less than 30 Kev in air) and becomes more predominant at higher energies in material of high atomic number.

In the Compton effect, the photon has an elastic collision with an orbital electron. After the collision, a photon of lower energy goes off in one direction, and the electron is projected with a definite energy in such a direction as to conserve energy and momentum. Absorption by the Compton effect is the predominant process for photons of medium energy.

In pair production, the incident photon completely disappears in the field of a nucleus with the production of an electron and positron pair. A positron is a particle equal in mass to the electron and having an equal but positive charge. The photon energy must exceed 1.02 Mev for this process to occur. Pair production is the predominant absorption process in all substances for gamma photons of the higher portion of the energy spectrum (above 5 - 10 Mev). Fig. 2.7 illustrates the photoelectric, the Compton, and the pair production processes.

The attenuation (absorption and scattering) characteristic of material is generally expressed in terms of linear attenuation coefficient, which is the reciprocal of thickness of material that reduces the intensity of an incident beam by $\frac{1}{e}$ or $\frac{1}{2.718}$ of its original value. This attenuation coefficient is determined by (a) photon energy, (b) the atomic number Z of the absorber, and (c) the density of the absorber.

The photon attenuation property of various materials is often given in half-or tenth-value layers, that is, the thickness of material which will reduce the photon intensity to one-half or one-tenth of the original

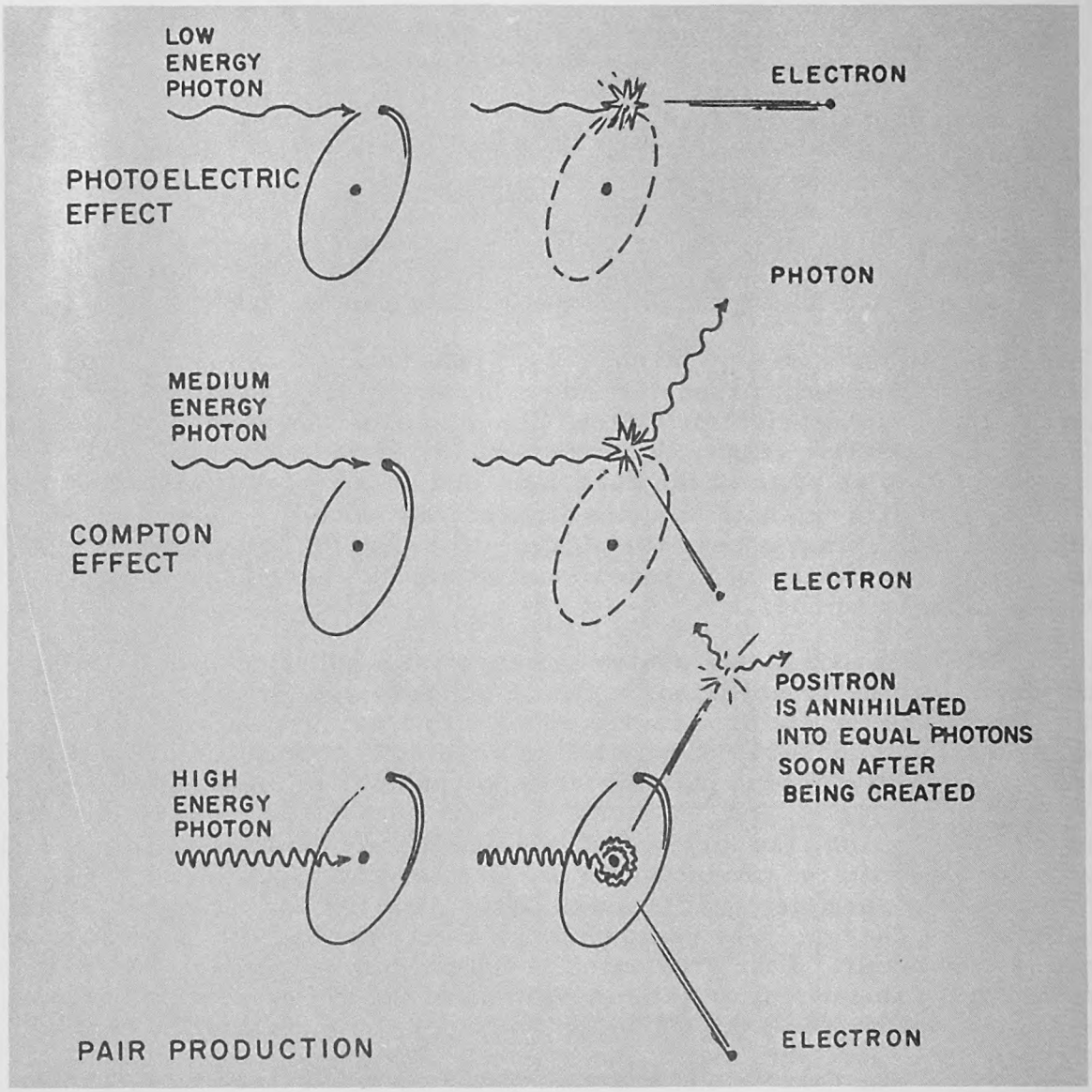


FIG. 2.7 ILLUSTRATION OF PHOTOELECTRIC, COMPTON, AND PAIR PRODUCTION PROCESSES

intensity respectively. A table of tenth-value layers for photon radiation of various energies may be found in Chapter 2, Volume II, while Fig. 2.8 is a graph of tenth-value thickness for various materials of density ρ. Fig. 2.8 does not include any build-up factor (see Appendix A of this Volume for the explanation of build-up factor).

NUCLEAR FISSION AND FISSION PRODUCTS

A. Nuclear Fission. Before the discovery of how nuclear energy could be released for destructive purposes, explosive material in bombs of the type in general use consisted largely of TNT or of a related chemical material. These explosive substances have the characteristic of being unstable; their breakup is associated with the liberation of a relatively large amount of chemical energy, mainly as heat. Once the decomposition of a few molecules of TNT has been initiated by means of a suitable detonator, the resulting energy release causes more molecules to decompose. As a result, the over-all rate at which TNT molecules break up is very high. This rapid breakup and its accompanying release of large amounts of energy in a relatively restricted volume results in an explosion.

A nuclear explosion differs from the chemical explosion in that the basic reaction taking place is not the mere rearrangement of molecules to form different compounds, but rather it is a rearrangement of the nucleons of the parent atom forming different atoms. This rearrangement releases many times the amount of energy released in a chemical rearrangement. Of the many nuclear reactions, the fission process is the basic nuclear reaction utilized in the nuclear bomb. Under suitable conditions, the fission reaction will produce very rapid liberation of large amounts of energy. The term fission is taken from the biological principle of cell reproduction by division into equal parts.

Nuclear fission is that nuclear transformation characterized by the splitting of a nucleus into two other nuclei and the release of a relatively large amount of energy. The heavy isotopes will fission when bombarded by suitable particles. The fissionable material in a nuclear bomb undergoes neutron-induced fission. U^{235} and Pu^{239} are examples of fissionable material that will split into two smaller fragments when bombarded by neutrons. In addition to the fission fragments, neutrons will also be ejected in the fission reaction. These neutrons may be used to induce more fission. Therefore, when a sufficient mass or quantity of fissionable material is assembled under the proper conditions, a neutron can be made to start a fission. This fission will produce fission fragments and two or more neutrons; these neutrons may then produce further fission, and so on, to give a chain reaction. A single neutron might thus cause the fission of a large quantity of U^{235}, just as the detonation of a few molecules of TNT might bring about the explosion of a large mass of TNT. Fig. 2.9 shows the basic reactions of a chemical and nuclear explosion. The chain reaction is illustrated in Fig. 2.10.

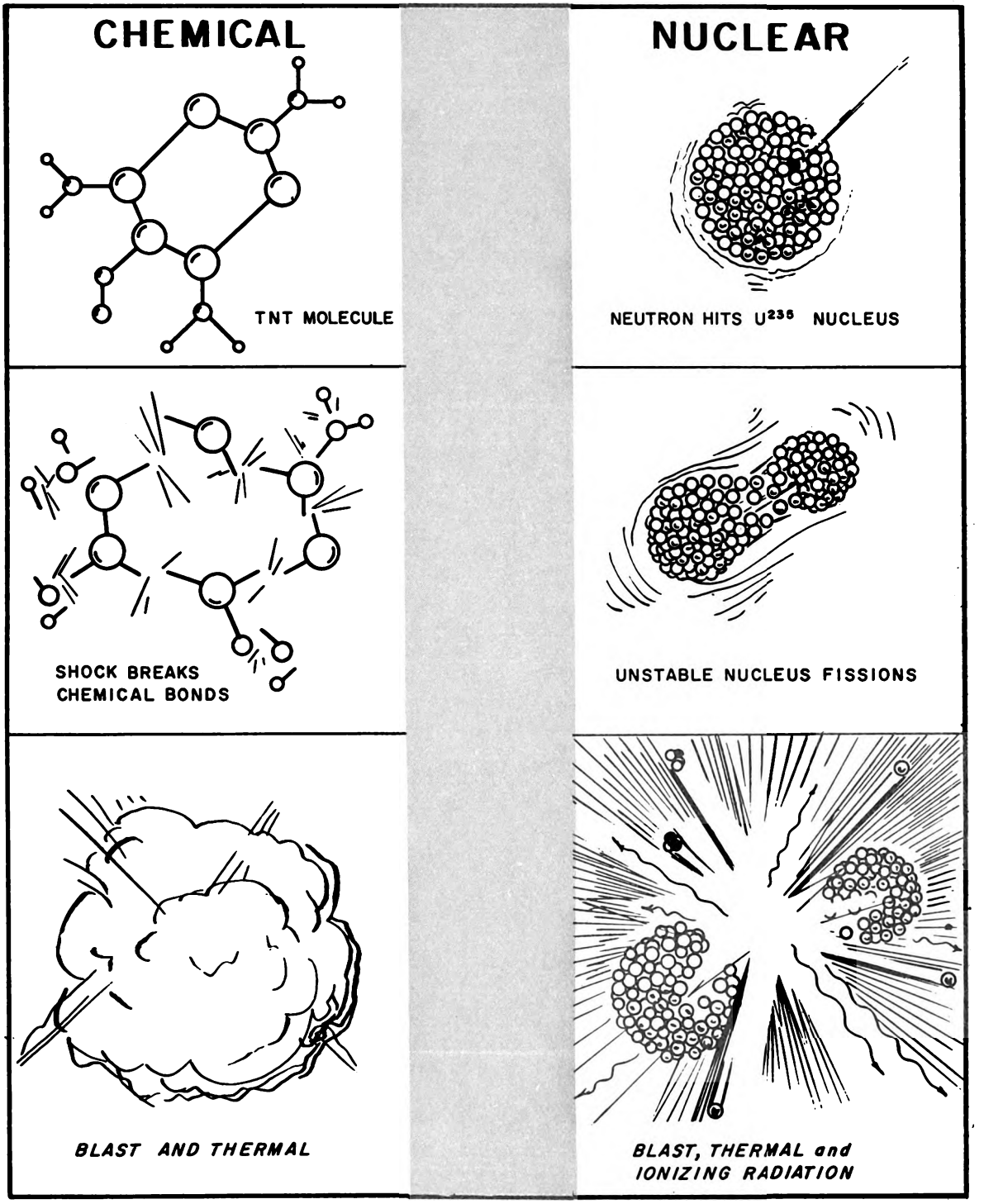


FIG. 2.9 ILLUSTRATION OF CHEMICAL AND NUCLEAR EXPLOSIONS

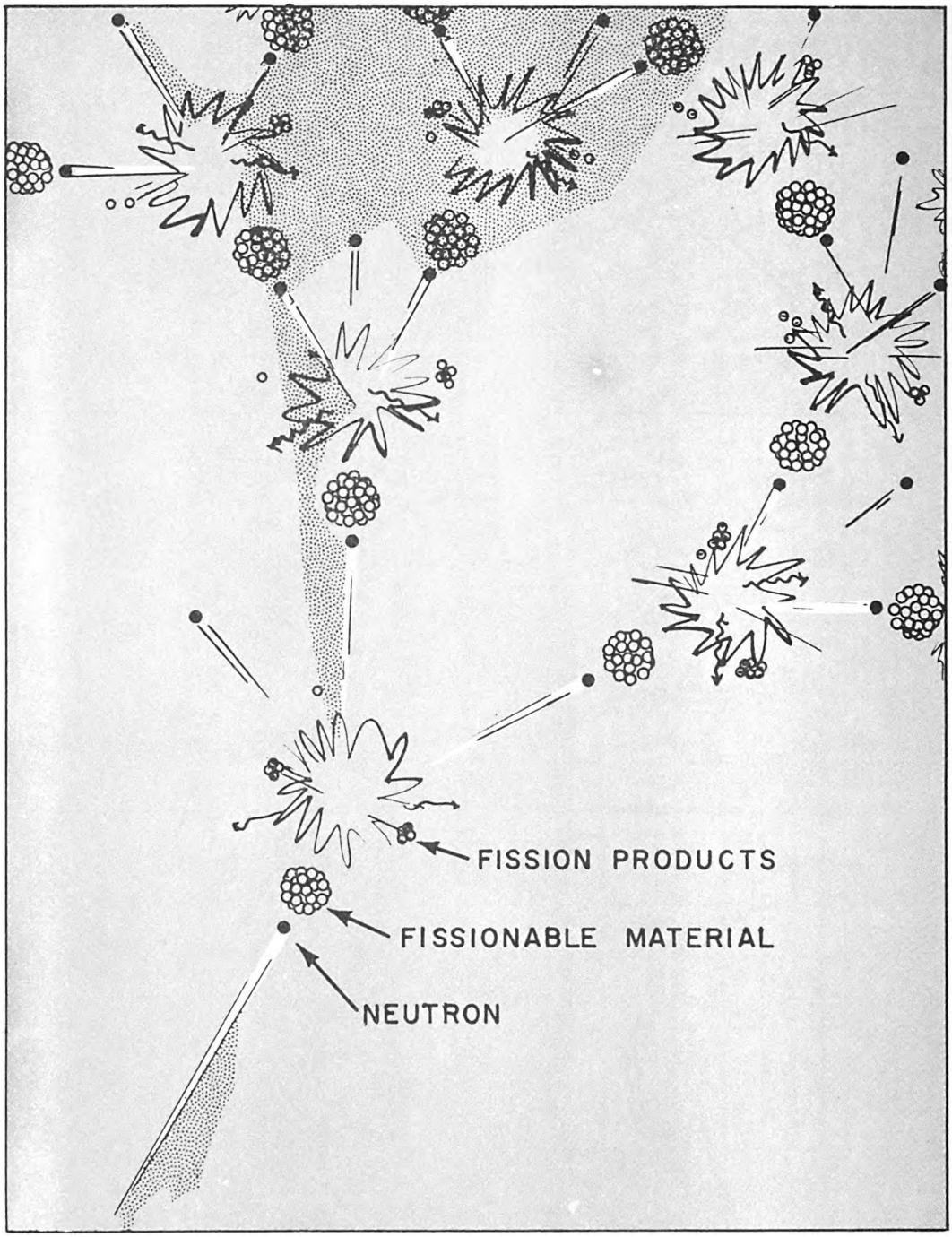


FIG. 2.10 ILLUSTRATION OF A NUCLEAR CHAIN REACTION

B. Fission Energy Release. The source of the tremendous energy released in a nuclear explosion is the transformation of matter into energy. When a fissionable nucleus splits into its fission products, it is observed that the sum of the mass of the products is less than the mass of the original atom, the resulting mass difference being converted into energy. When the U^{235} nucleus absorbs a neutron, it will fission, splitting in many different ways, but the products which are obtained in the greatest yield (approximately 6%) have mass numbers of 95 and 139. Let us consider the fission of U^{235} splitting into the Br^{90} and La^{143} fission products, assuming that three neutrons are also liberated. The symbolic formula for this fission is:

$$U^{235} + n^1 \longrightarrow (U^{236}) \longrightarrow Br^{90} + La^{143} + 3\,n^1 + \gamma$$

Br^{90} and La^{143} are both radioactive and their decay by beta emission is:

$$Br^{90} - \beta \longrightarrow Kr^{90} - \beta \longrightarrow Rb^{90} - \beta \longrightarrow Sr^{90} - \beta \longrightarrow Y^{90} - \beta \longrightarrow Zr^{90} \text{ (stable)}$$

$$La^{143} - \beta \longrightarrow Ce^{143} - \beta \longrightarrow Pr^{143} - \beta \longrightarrow Nd^{143} \text{ (stable)}$$

To calculate the energy liberated in the above fission, convert the mass difference to energy.

Fissionable Material		Fission Products	
U^{235}	= 235.117496 amu	Zr^{90}	= 89.932840
n	= 1.008986 amu	Nd^{143}	= 142.954052
		3n	= 3.026958
Total	236.126482 amu	Total	235.913850 amu
Mass difference	0.212632 amu		

But since 1 amu = 931 Mev, the energy liberated in this fission is 0.212632 amu x 931 Mev or 198 Mev. Thus, about 200 Mev of energy is released per fission of which 80% appears as kinetic energy of the fission products. The remaining 20% makes up the energies of the various ionizing radiations and decaying fission products.

C. Fission Products. When the uranium nucleus fissions, the uranium nucleus may split in many ways. More than 60 primary products have been detected. Each original fission product nucleus contains too many neutrons for stability and, hence, it undergoes various stages of beta decay with concurrent gamma emission before becoming a stable isotope. Since fission fragments start to decay at the time of formation, various decay products begin to accumulate and decay in

turn. The result is that within a short period of time nearly 200 different radioactive isotopes are in existence. Thus, it is easy to understand why the fission products will be highly radioactive and constantly emitting both beta and gamma rays.

In addition to the beta- and gamma-emitting isotopes created after a nuclear detonation, there is always some alpha-emitting material present in the bomb debris due to the unfissioned bomb material. Since the efficiency (that percentage of the fissionable material that undergoes fission) of a nuclear detonation is less than 100%, there will always be some alpha contamination mixed in with the fission product contamination. This alpha activity of unfissioned bomb material, such as uranium-235 and plutonium-239, will usually not be a personnel hazard when compared to the fission product activity, except possibly for low-yield detonations.

D. Fission Product Decay. Since there are some 60 different radioactive nuclides produced in the fission process and each, on the average, is the parent of two others, there are about 200 radioactive species present among the fission products after a short time. Although it is theoretically possible to express the rate of decay of this complex mixture in terms of the fission yields and their radioactive decay constants, it is quite impractical. The rate of decay of the fission products is, therefore, represented by the following empirical equation:

$$A = A_o t^{-n}$$

where A is the activity at any time t, A_o is the activity at zero or reference time, and n is a number that best represents the gross fission product decay.

A good working average of n is 1.2. It is adequate for planning dose and dose rate before an event, but the actual value of n should be confirmed by a decay plot of the actual fallout field. If the value of n is comparable to the above value, then the material can be expected to be fission product fallout.

Of more practical interest is the time dependence of the dose rate produced by fission product contamination. If we replace the activity A by the dose rate I, then the above equation becomes:

$$I = I_1 t^{-1.2}$$

where I = dose rate in r/hr at any time t

I_1 = dose rate at 1 hour after detonation

t = time after detonation in hours

These equations may be used to calculate radiation and contamination levels any time after detonation. Fig. 2.11 shows a plot of the t^{-n} decay for several values of n. Appendix A of this volume presents a $t^{-1.2}$ dose and dose rate decay table with sample problems. Chapter 2, Volume II, presents sample problems using the $t^{-1.2}$ plot for dose rate calculations. AFSWP-99, Dosage and Dose Rate Curves of Residual Radioactivity, presents graphical solutions for $t^{-1.2}$ decay.

NUCLEAR FUSION

In nuclear fusion, a pair of light nuclei unite or fuse together to form a nucleus of a heavier atom. An example is the fusion of the heavy hydrogen isotope, deuterium. Under suitable conditions, two deuterium nuclei may combine to form the nucleus of a heavier element, helium, with the release of energy.

Nuclear fusion reactions can be brought about by means of very high temperatures, and they are thus referred to as "thermonuclear processes." The actual quantity of energy liberated for a given mass of material depends on the particular isotope or isotopes involved in the fusion reaction. As an example, the fusion of all the nuclei present in one pound of deuterium would release roughly the same amount of energy as the explosion of 26,000 tons of TNT. In comparison, the complete fission of one pound of uranium or plutonium would produce as much energy as the explosion of 9,000 tons of TNT.

In certain fusion processes, neutrons of high energy are liberated. These can cause fission in uranium or plutonium. Consequently, association of the appropriate fusion reactions with a fissionable material will result in a more complete utilization of the latter for the release of energy. A device in which fission and fusion (thermonuclear) reactions are combined can therefore produce an explosion of great power.

Four thermonuclear fusion reactions appear to be of interest for the production of energy because they are expected to occur sufficiently rapidly at realizable temperatures. These are:

a. $H^2 + H^2 \longrightarrow He^3 + n + 3.2$ Mev

b. $H^2 + H^2 \longrightarrow He^3 + H^1 + 4$ Mev

c. $H^3 + H^2 \longrightarrow He^4 + n + 17$ Mev

d. $H^3 + H^3 \longrightarrow He^4 + 2n + 11$ Mev

Without going into detail, it may be stated that the fission of a nucleus of uranium or plutonium having a weight of nearly 240 amu releases about 200 Mev. This may be compared with an average of about 24.2 Mev obtained from the fusion of five deuterium nuclei with a weight of 10 amu. Weight for weight, the fusion of deuterium nuclei would produce nearly three times as much energy as the fission of uranium or plutonium.

In order to make fusion reactions take place, temperatures in the order of a million degrees are necessary. One way in which such temperatures can be obtained is by means of a fission explosion. Consequently, by combining a quantity of deuterium or tritium with a fission bomb, it should be possible to initiate one or more of the thermonuclear fusion reactions given above. If these reactions, accompanied by energy evolution, can be propagated through a volume of hydrogen isotope, a thermonuclear explosion may be realized.

It may be noted that the two reactions involving tritium are of particular interest for several reasons. Not only do they occur more rapidly and produce more energy than those of deuterium but, in addition, one or two neutrons are emitted in each case. These neutrons are able to contribute to the fission of uranium and plutonium, thus adding to the total energy release of the combined fission-fusion system.

The fallout material from a thermonuclear weapon is expected to be the same as from a fission weapon. The majority of the radioactive fallout material comes from the fission products of the fission component. Some radioactive fallout comes from the activity induced in material at and near ground zero and subsequently taken up in the cloud. Although more induced activity would be expected from a fusion weapon than from a fission weapon, the fission product decay calculations presented in the foregoing sections are applicable to fallout from a fusion weapon.

TYPES OF BURSTS

A nuclear weapon burst produces a characteristic amount of fission products as determined by the weapon's design. If the weapon is detonated near or on the earth's surface, a large portion of the fission products will fall out locally producing a radiation and contamination hazard. If the weapon is detonated above the earth's surface, little or no (dependent upon burst height) fission products will fall out locally. The fission products will be mixed and stored for several weeks in the troposphere or stored for tens of years in the stratosphere. The short-lived materials will decay while up in the atmosphere and the longer-lived materials will fall out over a much larger area of the earth's surface, producing no militarily significant radiological hazard. Thus, nuclear weapon bursts may be categorized as either contaminating or non-contaminating.

The relative importance of the sources of radioactive contamination following a nuclear explosion will depend on a variety of circumstances. The nature of the surrounding terrain and the height of the burst are perhaps of most significance, since the height above the ground determines the contamination potential of any given burst. The contamination potential of a

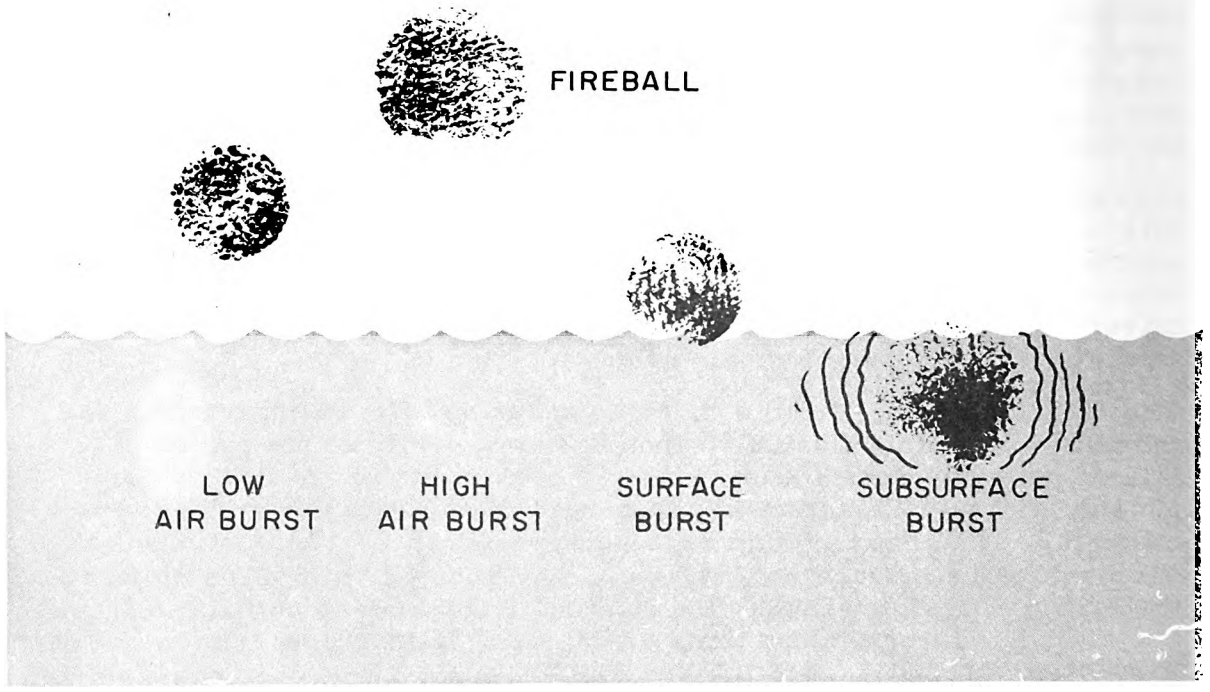


FIG. 2.12 CLASSIFICATION OF NUCLEAR BURSTS

detonation depends primarily on the fallout and the fallout depends on the debris of various kinds sucked up or thrown up from the earth's surface. In a sufficiently high air burst, relatively little extraneous material is taken into the cloud and the local fallout is minor when compared to a surface or sub-surface burst. The local fallout is much more significant for surface and sub-surface bursts. Although it is impossible to make a sharp demarcation, it is usually assumed that an air burst is one in which the fireball of the burst does not touch the surface of the earth. A surface burst is one in which the fireball touches the surface of the earth, while a sub-surface burst is one where the fireball is not visible above the surface of the earth. Fig. 2.12 illustrates the various types of bursts.

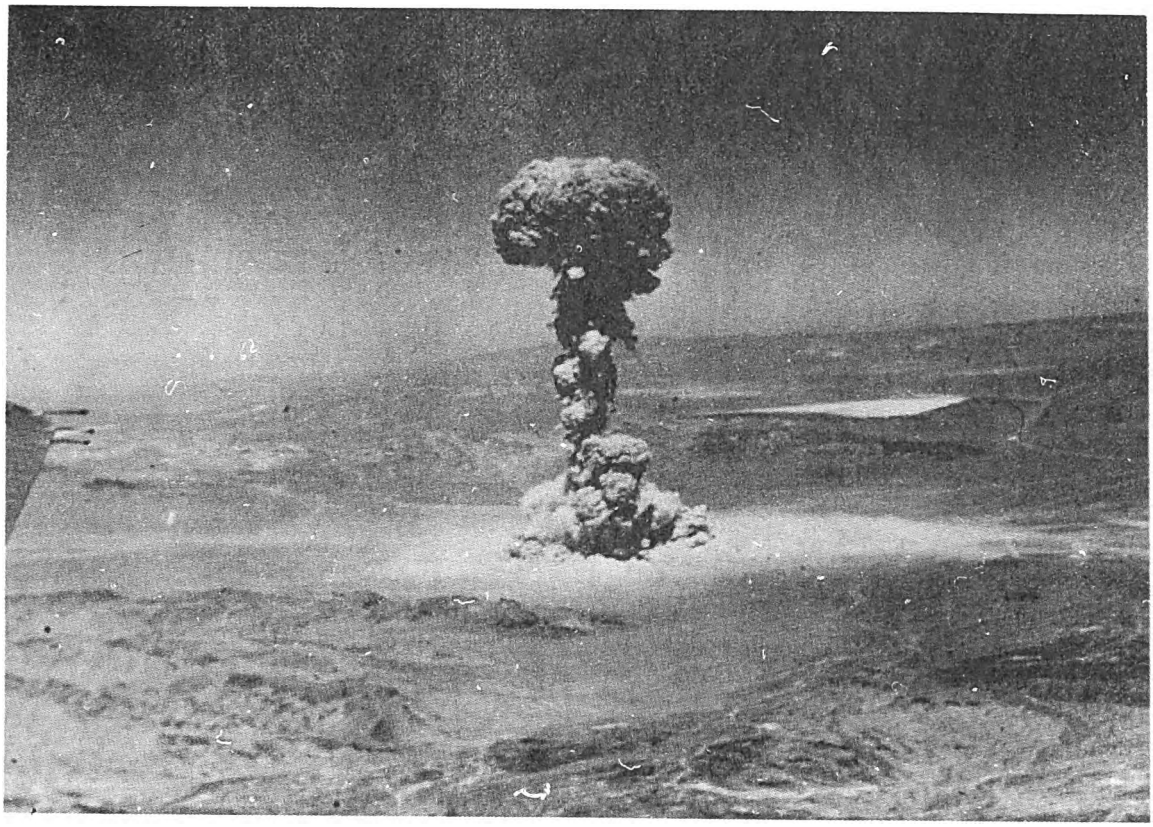
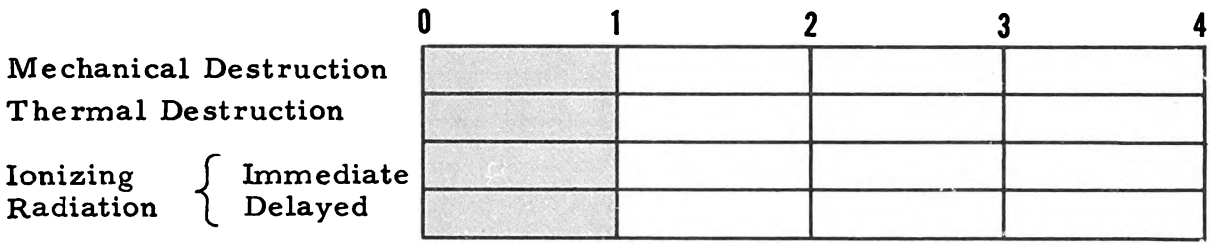


FIG. 2.13 LOW AIR BURST



In a low air burst, at the instant of explosion, the atomic bomb emits ionizing radiations consisting of gamma rays and neutrons. Thereafter nuclear radiations consist of gamma and beta radiation from the fission products and alpha radiation from the unfissioned bomb material. Radioactive contamination consists of fission products, unfissioned bomb material, and induced radioactivity which travel with the bomb cloud and fall out to the surface of the earth at some later time. The neutron-induced activity will be significant only around ground zero, and its magnitude will depend upon the height and type of burst.

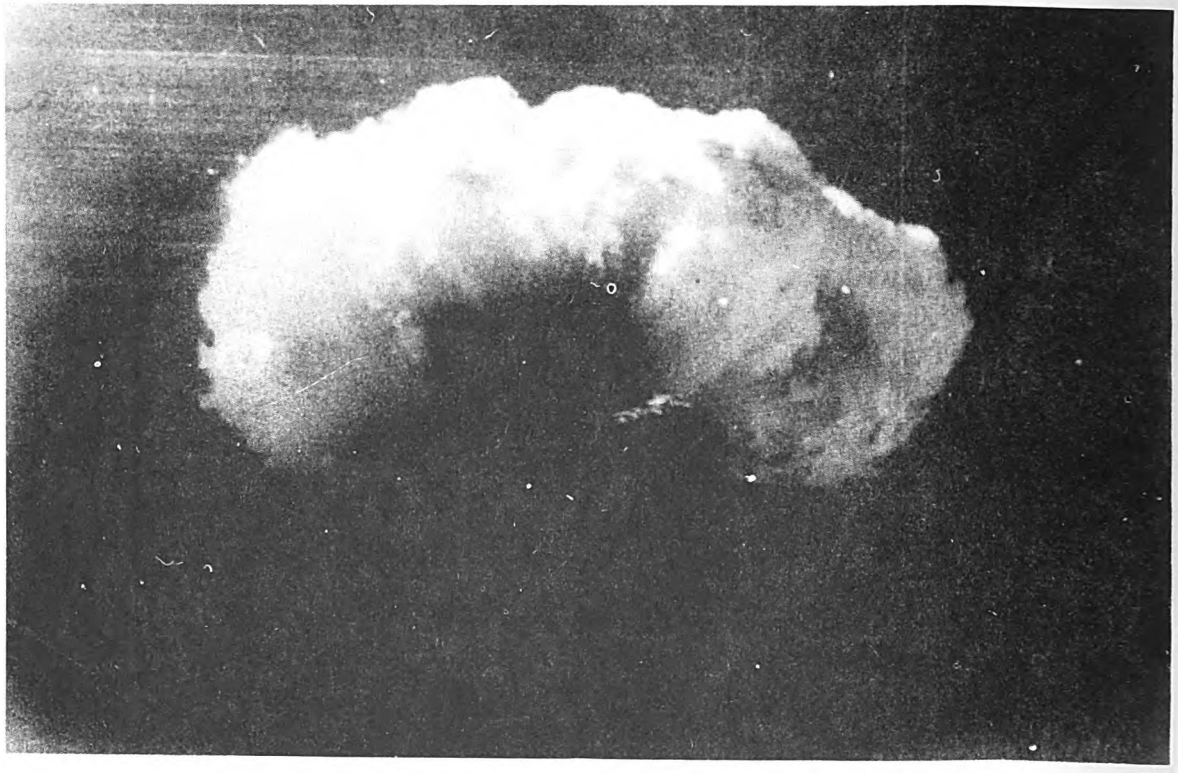
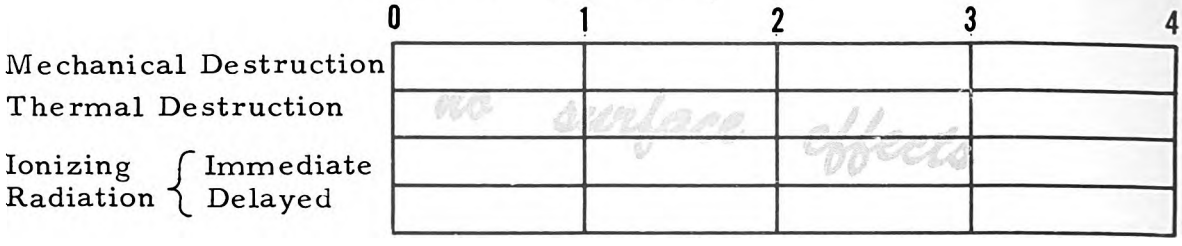


FIG. 2. 14 HIGH AIR BURST



The radiation hazard produced by the fallout and soil-induced activity will depend upon the size and yield of the weapon, height above ground, and meteorological conditions. If the fission products do not attach themselves to large particles, they will stay aloft longer and, in effect, be "diluted" while decaying in the atmosphere before falling out to the earth's surface. Figs. 2. 13 and 2. 14 illustrate a low and high altitude air burst. The high air burst may be considered one where the point of detonation is several fireball diameters above the surface of the earth. The bar graph classifies the relative effects, assuming the low air burst effects as the unit of measurement.

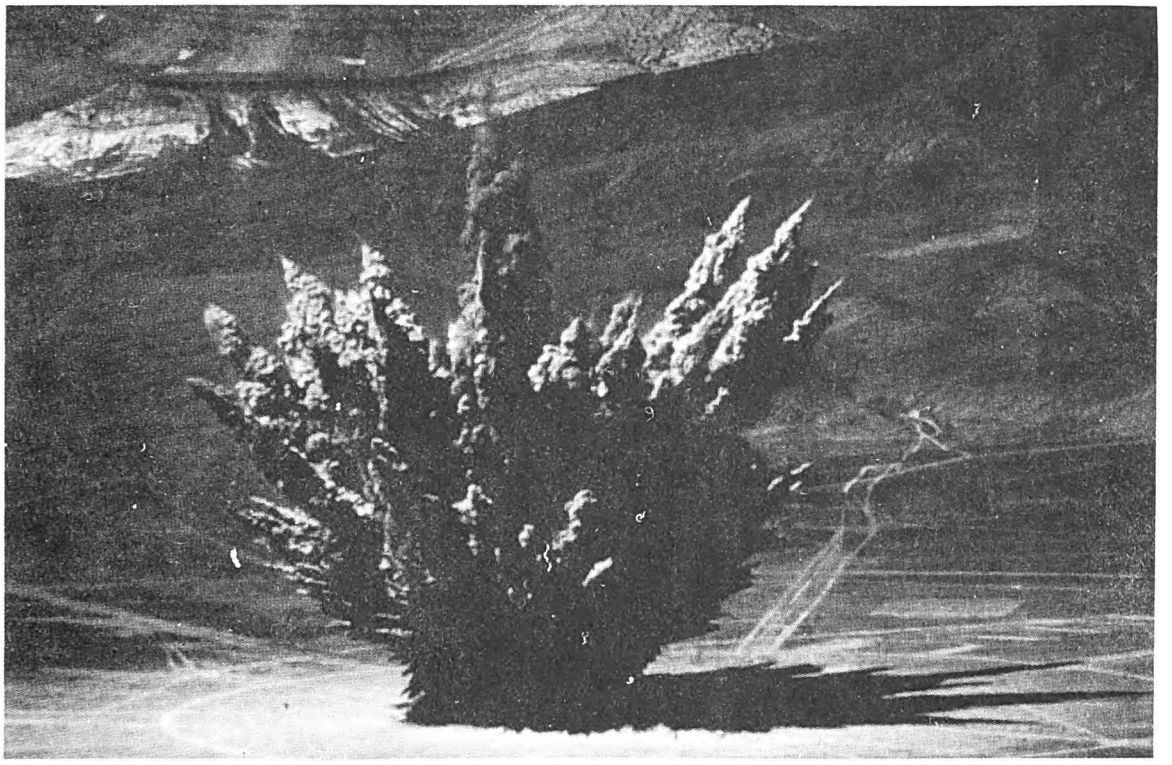
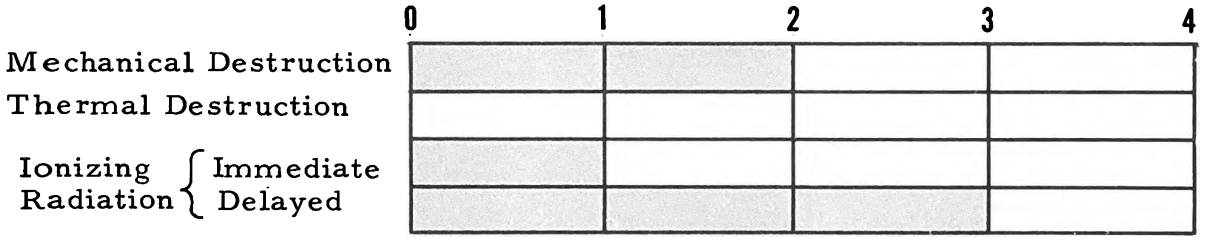


FIG. 2. 15 SUB-SURFACE BURST



In the case of a surface or sub-surface burst, it is reasonably certain that there is contamination due to neutron-induced activity. However, the amount of induced activity will be a small percentage of that produced by fission products. The formation of a large crater is accompanied by the throwing into the air of considerable amounts of dirt contaminated with fission products and with radioactive isotopes formed by neutron capture. This airborne activity which produces a significant fallout constitutes a serious hazard in areas downwind from the explosion. A surface or sub-surface burst results in much greater radioactive contamination around ground zero when compared to an air burst. Fig. 2. 15 illustrates a sub-surface or underground burst while Fig. 2.16 illustrates a surface burst. The bar graphs classify the effects relative to the low air burst.

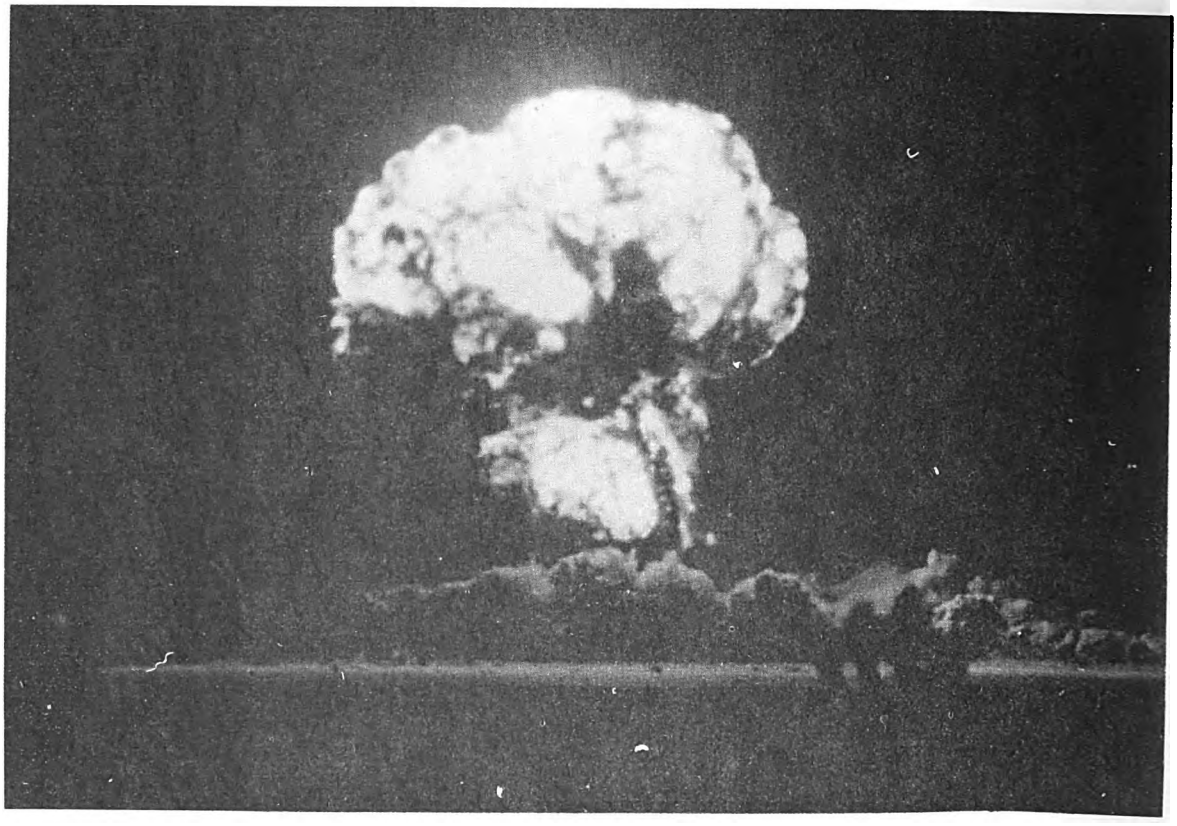
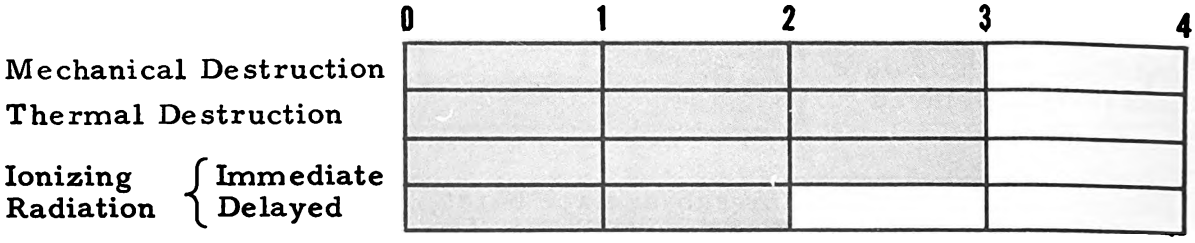


FIG. 2. 16 SURFACE BURST



For an underwater burst at moderate depth, the initial gamma and neutron radiations can be ignored since they are almost completely absorbed in the water. The residual contamination is due largely to the fission products which do not escape as easily as they do in the case of a surface or low air burst. The induced activity such as radioactive sodium, manganese, and chlorine will be masked by the much greater amount of fission product activity. It is estimated that almost all of the fission product activity either remains in the water or falls back in the form of a ra-

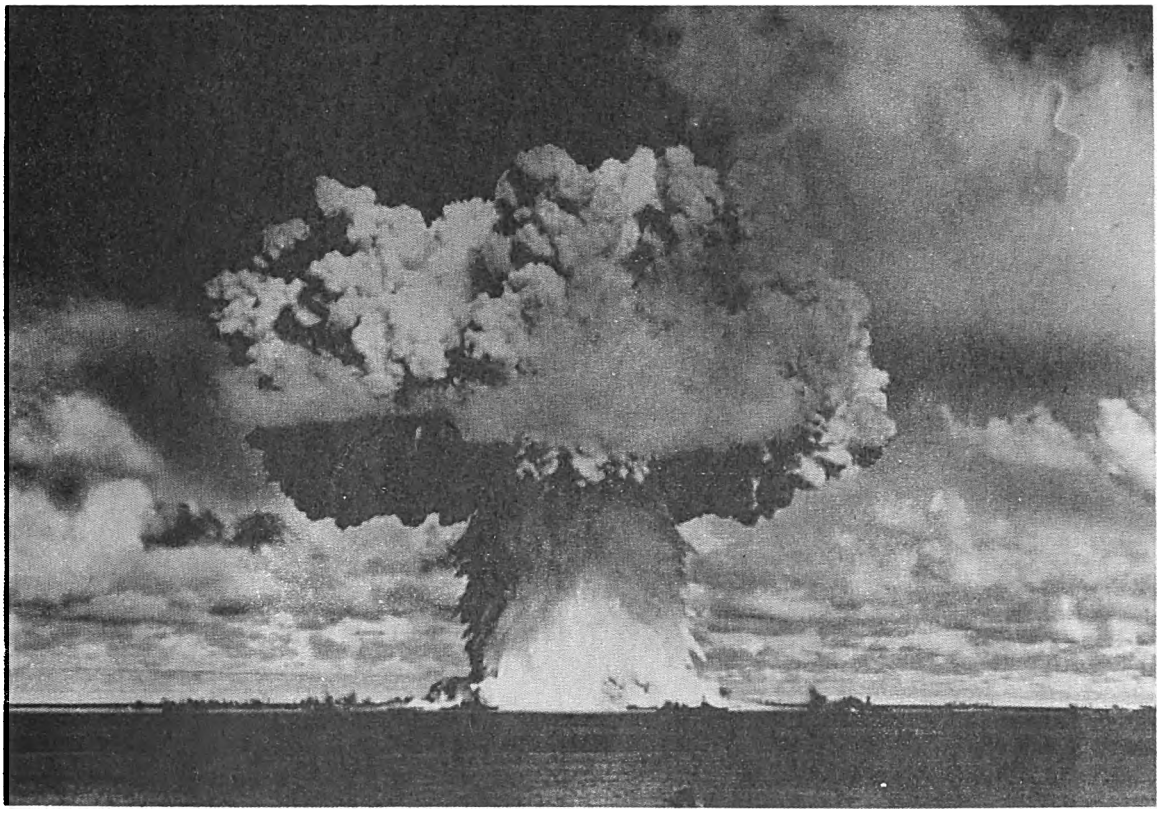
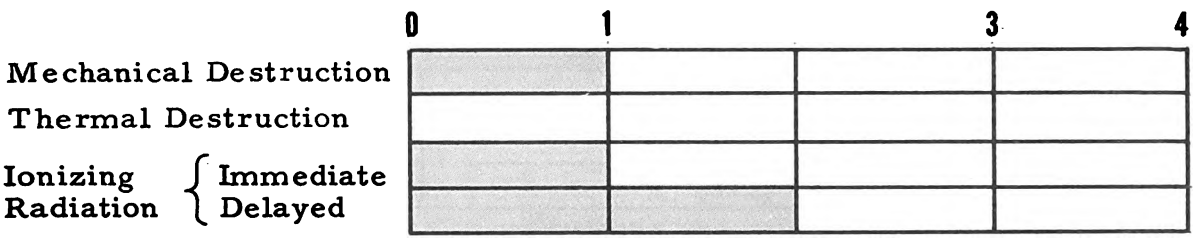


FIG. 2. 17 SHALLOW UNDERWATER BURST



dioactive base surge and rain with the concentration being diluted by currents or settling. The extent and degree of contamination following an underwater nuclear burst will probably vary markedly, depending upon such phenomena as the base surge, rainout, height of cloud, etc., which in turn may well depend upon the depth of the burst, the meteorological conditions, and the topography at the site of the detonation. Figure 2. 17 illustrates a shallow underwater burst.

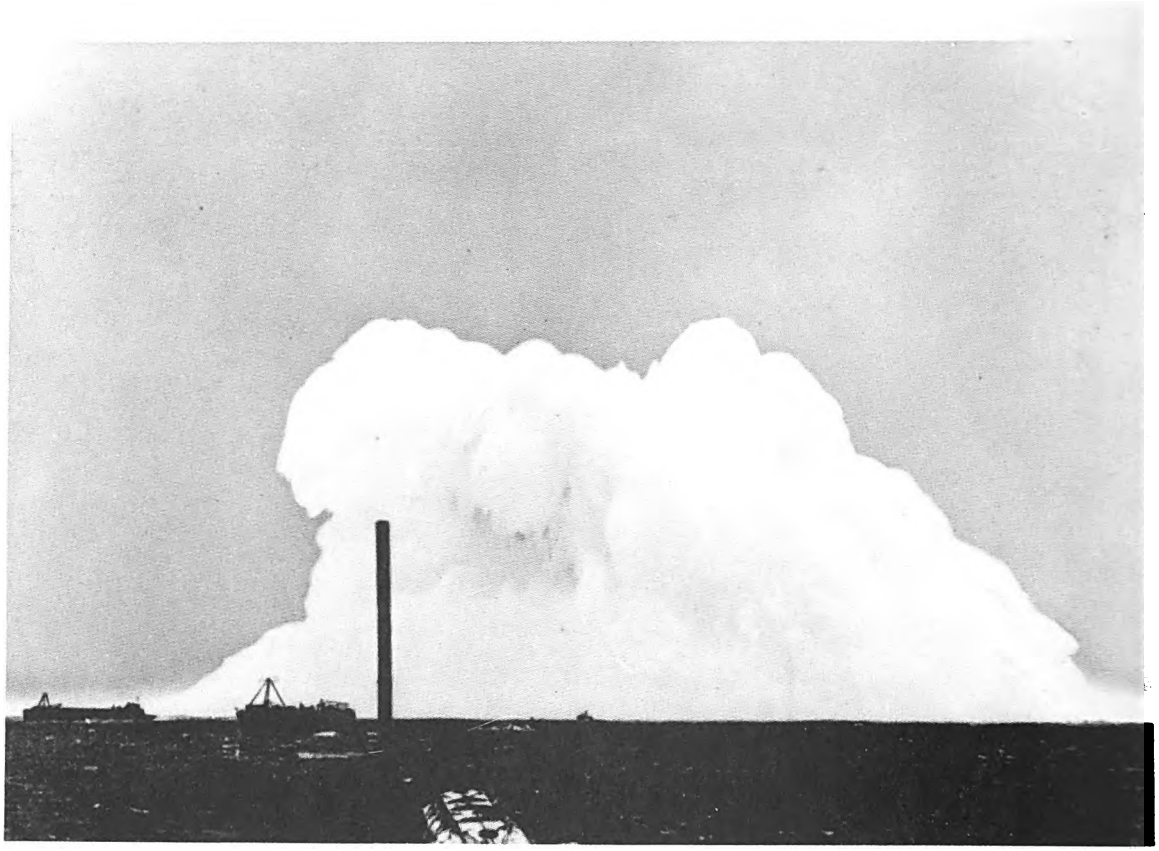
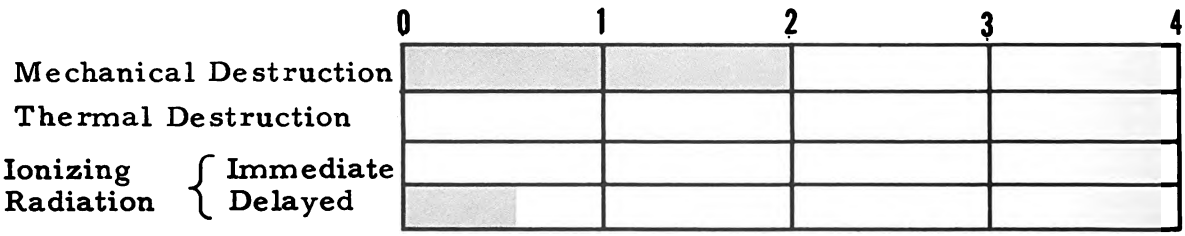


FIG. 2.18 DEEP UNDERWATER BURST



In a deep underwater burst, Fig. 2.18, the fireball forms a hot gas bubble consisting of the bomb detonation products, plus large quantities of steam. This bubble, in rising to the surface, pulsates, and, in so doing, loses some of its radioactivity in deep layers. To what extent it retains its identity as it approaches the surface is not known but, in these circumstances, there is no large cylindrical column of water and no well-defined visible "atomic cloud." A large fraction of the radioactivity is contained in the foam or froth in a circular region directly above the detonation point. There appears to be no extensive fallout, but the drifting mist may be dangerously radioactive within a few miles of SZ. Also the deposition of highly radioactive foam on a nearby shore would be hazardous.

INITIAL AND RESIDUAL NUCLEAR RADIATIONS

The explosion of a nuclear weapon is accompanied by the emission of nuclear radiation consisting of gamma rays, neutrons, beta particles, and a small proportion of alpha particles. The neutrons and some of the gamma rays are emitted in the actual fission process, that is to say, simultaneously with the explosion, while the remainder of the gamma radiation and the beta particles are liberated as the fission products decay. The alpha particles result from normal radioactive decay of the plutonium-239 or uranium-235 which has not undergone fission. The efficiency of the bomb is that percentage of the fissionable material which has fissioned. Thus, a low-efficiency detonation would have more alpha emitters in the contamination than would a high-efficiency detonation.

The ionizing radiations emitted from a nuclear detonation are described as initial radiation and residual radiation. Initial nuclear radiation refers to all the nuclear radiation emitted in the first minute following detonation. All the neutron radiation is also delivered within the first minute after detonation. It is to be noted that the initial radiation includes some alpha and beta radiation, but because the ranges of alpha and beta radiation are relatively short when compared to the initial gamma and neutron radiation, only the gamma and neutron radiation need be considered for defense purposes. The residual radiation, i.e., the radiation continuing from 1 minute after detonation to infinity, is due to fission products, fission decay products, induced activities, and alpha radiation from the unfissioned bomb material. This radioactive material that settles to the earth's surface is called fallout.

INDUCED ACTIVITY

A source of residual nuclear radiation which might be significant in the event of a low air burst is caused by the radioactivity induced in the earth's surface material by the neutrons produced at time of fission. In a surface or sub-surface burst, these induced radioactive elements add but a small fraction to the residual contamination and are found only in the immediate vicinity of the detonation point. In passing, it should be mentioned that, of the various types of ionizing radiation produced in a nuclear detonation, only the neutron radiation is capable of transforming stable elements into radioactive elements. Nearly all known stable elements exhibit the radiative capture reaction with neutrons. In the radiative capture reaction, the neutron will be captured by the nucleus of an element and often transforms the element into a radioactive element which then emits ionizing radiations.

Perhaps the induced radioactivity which deserves most attention is that which is produced in sodium. Although sodium is present to the extent of about 0.2% in average soil, calculations indicate the possibility of the formation of appreciable amounts of radioactive sodium-24. This isotope has a half-life of 14.8 hours. It emits beta particles with average energy of approximately 0.5 Mev but, more important, it emits gamma rays of 1.4 and 2.8 Mev energy. The activity of the radiosodium would be added to that of any fission product that might be present. The fission products do not include radioactive sodium. However, appreciable amounts of radioactive sodium could be detected in the presence of fission products by the difference in decay rates.

Apart from interaction with materials contained in the soil, the neutrons from an atomic bomb might be captured by other atomic nuclei such as those contained in building structures and other objects. Of these, probably zinc and copper and, to a lesser extent, the manganese hardening agent in steel are most likely to undergo neutron capture. Wood and clothing are unlikely to develop appreciable induced activity, but glass might become radioactive because of the presence of sodium.

In the event of an underground atomic explosion, a large proportion of the neutrons released would probably be captured by the elements present in the soil, leading to the formation of quantities of radiosodium, radiomanganese, etc. At the same time, a considerable fraction of the fission products would remain in the vicinity of ground zero so that the residual nuclear radiation would be very large in the immediate vicinity of the burst. The greater majority of the residual radiation would be due to this restricted fallout.

Since sea water contains some 3% of sodium chloride, a surface detonation, and more particularly an underwater detonation, produces measurable amounts of radioactive Na^{24}. In addition, the radioisotope of chlorine, mass number 38, is formed with a much shorter half-life, namely, 38.5 minutes. However, the fission product contamination in or above the water is the major radiation hazard.

RADIOACTIVE FALLOUT

In an air burst where the fireball does not touch the earth's surface, the radioactivity produced in the bomb condenses on particles from the bomb's casing and on dust which happens to be in the air. These minute particles may settle to the surface over a very wide area, probably spreading around the world over a period of days or even months. By the time these fine particles reach the earth's surface, the major part of their radioactivity will have dissipated in the atmosphere, and the residual contamination will be widely dispersed.

In a surface or sub-surface burst, the contamination potential from the fallout is greatly increased because of the debris forced up and spread by the cloud. The following description of the fallout pattern of the thermonuclear device fired at the Bikini Atoll on March 1, 1954 is given as an example of the magnitude of radiation hazard from fallout.

"The very large thermonuclear device fired at the Bikini Atoll on March 1, 1954, was exploded on a coral island. Coral consists of calcium carbonate; thus, the detonation's radioactivity was spread by particles consisting largely of unslaked lime which, during the hours of descent, was slaked by moisture in the atmosphere. These particles ranged between 1/1000th and 1/50th of an inch in diameter and were, on the average, somewhat adhesive. The prevailing winds were westerly, so the bomb cloud moved generally to the east and deposited the radioactive particles in varying amounts over an elliptical or cigar-shaped area. About 160 (statute) miles downwind from the point of burst, the early fallout was observed in the form of fine particles which looked like snow. Fallout began there about eight hours after the detonation and continued for several hours.

"The test explosion, at ground surface, contaminated a cigar-shaped area extending approximately 220 statute miles downwind and varying in width up to 40 miles . . . .

"Data from this test permits estimates of casualties which would have been suffered within this contaminated area if it had been populated. These estimates assume: (1) that the people in the area would ignore even the most elementary precautions; (2) that they would not take shelter but would remain out of doors completely exposed for about 36 hours; (3) that in consequence they would receive the maximum exposure. Therefore, it will be recognized that the estimates which follow are what might be termed extreme estimates since they assume the worst possible conditions.

"On the basis of data from this and other tests, it is estimated that, following the test explosion on March 1, 1954, there was sufficient radioactivity in a downwind belt about 140 miles in length and of varying width up to 20 miles to have seriously threatened the lives of nearly all persons in the area who did not take protective measures. . . . Inside Bikini Atoll, at a point 10 miles downwind from the explosion, it is estimated that the radiation dose was about 5000 roentgens for the first 36 hour period after the fallout. The highest radiation measurement outside of Bikini Atoll indicated a dose of 2300 roentgens for the same period. This was in the northwestern part of the Rongelap Atoll, about 100 miles from the point of detonation. Additional measurements in Rongelap Atoll indicated doses, for the first 36 hour

period, of 2000 roentgens at 110 miles, 1000 roentgens at 125 miles and, farther south, only 150 roentgens at 115 miles from Bikini.

"Some distance farther from the point of detonation, at about 160 miles downwind and along the axis of the ellipse, the amount of radioactivity would have seriously threatened the lives of about one-half of the persons in the area who failed to take protective measures. It is estimated that the radiation dose at that point was about 500 roentgens for the first 36 hour period.

"Near the outer edge of the cigar-shaped area, or approximately 190 miles downwind, it is estimated that the level of radioactivity would have been sufficient to have seriously threatened the lives of 5 to 10% of any persons who might have remained exposed out of doors for the first 36 hours. In this area the radiation dose is estimated at about 300 roentgens for the first 36 hour period.

"Thus, about 7000 square miles of territory downwind from the point of burst was so contaminated that survival might have depended upon prompt evacuation of the area or upon taking shelter and taking other protective measures.

"At a distance of 220 miles or more downwind, it is unlikely that any deaths would have occurred from radioactivity even if persons there had remained exposed up to 48 hours and had taken no safety measures.

"The estimates cited above do not apply uniformly throughout the contaminated area inasmuch as the intensity of radioactivity within a region of heavy fallout will vary from point to point due to such factors as air currents, rain, snow, and other atmospheric conditions. Because of this and because most persons, if given sufficient warning, probably would evacuate the area or take shelter and other precautionary measures, the actual percentage of deaths could reasonably be presumed to be considerably smaller than these extreme estimates."*

BLAST AND THERMAL EFFECTS

The blast and thermal effects of a nuclear detonation are immediate effects of the detonation. The explosion is followed by the formation of a shock wave, moving outward at high speed. The overpressure in the shock wave and the accompanying wind (following the negative pressure phase) are responsible for the blast damage to structures.

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*Abstracted from the AEC news release of 15 Feb. 1955, "The Effects of High-Yield Nuclear Explosions."

Thermal radiation is emitted from the fireball of a nominal weapon in two pulses. The first pulse lasts for little more than 0.01 second and emits a large portion of the ultraviolet radiation. The second pulse lasts up to 3 seconds and carries most of the thermal energy emitted by the weapon, which consists mainly of visible and infra-red rays. Except near ground zero, it is the second pulse which is responsible for skin burns and some incendiary action. The magnitude and duration of the thermal effects have to be scaled up for super weapons.

Since the scope of this manual is radiation and contamination control, reference is made to The Effects of Nuclear Weapons, June 1957, for more detailed information about the effects of nuclear weapons.

CHAPTER 3

RADIATION INSTRUMENTS AND DOSIMETERS

Since ionizing radiations cannot be detected by the human senses, man must rely on an electronic or chemical device to perform this task. Because of the different physical properties of the various types of radiation and because of the wide range of possible radiation levels, there is no single radiation detection instrument that is capable of monitoring all radiological situations. Therefore, radiological safety personnel must be able to choose from and operate various devices to properly evaluate a radiological situation. Appendix B of Volume II presents detailed procedures for the operation of various radiacs.

In general, the characteristics (types and levels of radiation that can be measured) of a radiation detection instrument may be obtained from an inspection of the instrument. Any radiation to be detected must reach the detection element; therefore, alpha particles which have low penetrating power would require a very thin window or a windowless area on the detector, and beta particle detection would require a relatively thin window (1/32 in. plastic) to be efficient at most beta energies. Since gamma rays and neutrons can penetrate relatively thick detector walls, gamma ray and neutron particle detection instruments may have relatively thick walls on or around the radiation sensitive element.

THEORY OF DETECTOR OPERATION

The major portion of radiation detection instruments operate by directly measuring the ionizing effects of radiation. Instruments that measure the chemical effects produced by the ionization will also be discussed.

A. Ion Chambers. An ionization chamber consists of two conductors which are insulated from each other. The space between the two conductors is filled with a gas (air or special mixtures) upon which is impressed an electric field produced by raising the potential of one conductor over the other. Fig. 3.1 shows a simplified schematic diagram of an ion chamber survey instrument.

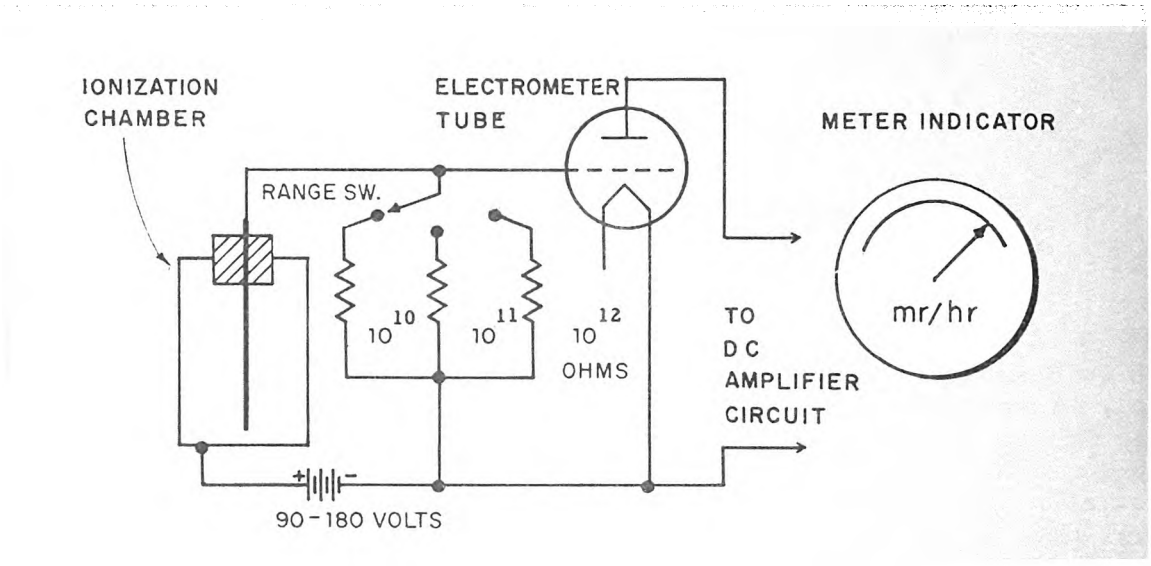

FIG. 3.1 SIMPLIFIED SCHEMATIC OF AN ION CHAMBER RADIAC

When the ionization chamber is in a radiation field, the photons (X or gamma rays) or charged particles (alpha and beta) ionize the gas between the two electrodes, and these ions are attracted to the electrodes causing a flow of current. The magnitude of this current is proportional to the radiation dose rate and is measured by suitable electrometer circuits. The chamber wall material and thickness and filling gas mixture will determine the response of the instrument to the various types and energies of radiation. The electronic component provides a readout for the signal produced by the ionization chamber.

Fig. 3.2 shows the relationship between the charge collected as a function of the collection voltage and the various counting regions. The curve also shows the various operating regions: ion chamber region, proportional region, and Geiger region. It will be noted that in the ionization chamber region the current flow is a measure of the ionization and that the physical construction of the chamber determines the radiation to be detected since any ionization occurring within the chamber will cause current flow.

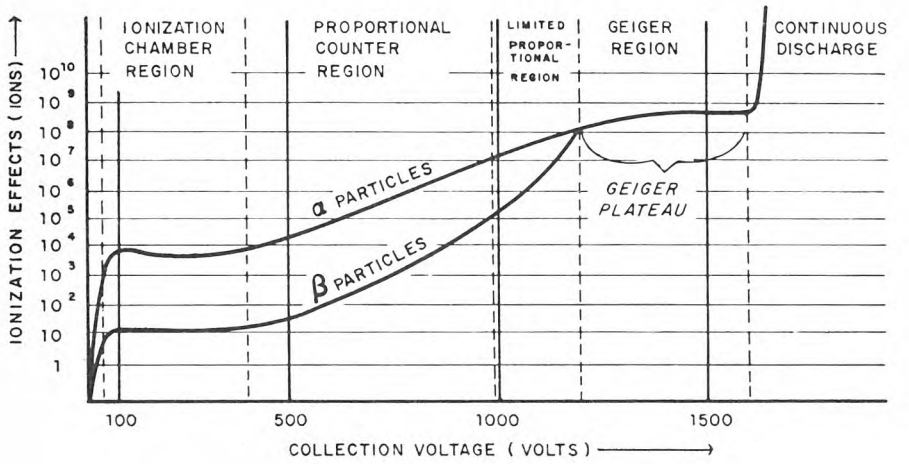

FIG. 3.2 CURVE SHOWING RELATIONSHIP BETWEEN THE CHARGE COLLECTED AS A FUNCTION OF COLLECTION VOLTAGE AND THE VARIOUS COUNTING REGIONS

B. Proportional Counters. A section of the curve shown in Fig. 3.2 is called the proportional counter region. In the proportional region, photons or particles entering the counter produce a pulse of M times the original ionization produced in the gaseous material. (M is dependent upon the operating potential of the proportional counter.) The size of the electronic pulse produced will be proportional to the number of primary ions produced, an alpha pulse being greater than one produced by a beta particle or photon. The proportional counter can be used to differentiate between the various types of radiations by adjusting the electronic circuit of the instrument to accept only pulses of a certain magnitude. For example, beta particles may be differentiated from alpha particles since the alpha particle is a doubly-positive-charged particle and produces more ionization within the chamber than the beta particle, resulting in a larger output pulse. Proper setting of the pulse height selector will bias out the smaller pulses produced by beta particles or gamma photons.

C. Geiger-Mueller Counters. The G-M counter consists basically of a cylindrical cathode with a coaxial wire anode mounted in its center and is therefore essentially a cylindrical ionization chamber. If the voltage of the chamber is slowly increased, various operating characteristics are obtained. At moderate voltages, the tube acts as an ion chamber in which one photon or particle produces one pulse. At a higher voltage, the proportional region is obtained. In the proportional region, one photon or particle entering the counter produces one pulse with an amplitude M times as large as that which would be produced in the ion chamber region. (The factor M depends upon the operating voltage.) If the anode voltage is further increased, the proportionality feature gradually disappears, and all pulses at a given anode voltage become the same size no matter what the initial ionization. This portion of the curve is called the Geiger region. At still higher voltages, the tube discharges continuously as in a neon tube (arc discharge). (See Fig. 3.2.)

When an ionizing particle passes through a G-M tube operating in the Geiger voltage region, a certain number of ion pairs are formed (negative and positive ions). The free electrons produced by the ionizing particles are accelerated in traveling toward the anode and further ionize the gas in the G-M tube, eventually producing an avalanche of electrons which are collected at the anode, producing the output pulse. This avalanche action is a phenomenon of gas amplification and is the mechanism whereby equal sized pulses are produced in G-M tubes from ionizing particles of various energies. Fig. 3.3 demonstrates the electron multiplication or avalanche in a G-M tube.

Because the electrons released in ionization have less mass than the positive ions, they will reach the anode before the positive ions reach the cathode. Precaution must be taken so that when the positive ions reach the cathode a second pulse will not be generated. The quenching gas (alcohol-argon mixture or halogen) with which the tubes are filled performs this function. For example, in an alcohol-argon filled tube, when a positively charged alcohol ion of the quenching gas comes to within 10^{-7} or 10^{-8} cm of the cathode, it pulls an electron from the cathode material by field emission; this electron neutralizes the ion, leaving an excited molecule. The molecule later loses its excitation by dissociating into two uncharged atomic groups resulting in no ion formation. Thus the positive ions are neutralized before reaching the cathode, and no second pulse is produced from the initial ionizing event.

The life of an alcohol-argon filled G-M tube is normally around 10^{8} counts or 100 days of continuous operation at 100 counts/sec. Some G-M tubes

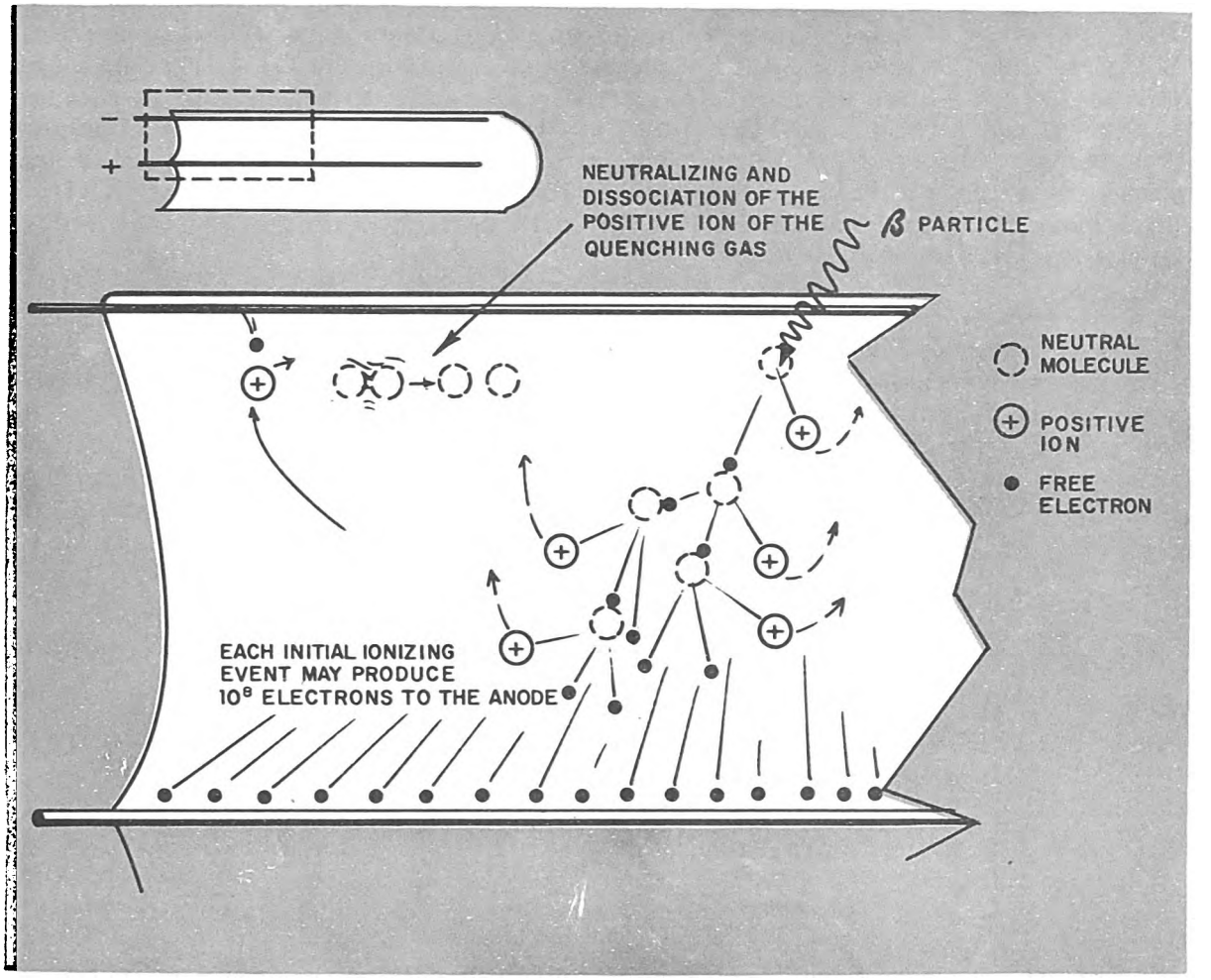

FIG. 3.3 ELECTRON MULTIPLICATION IN A G-M TUBE

are filled with halogen gas which performs the quenching action but does not dissociate; therefore, these tubes have an indefinite life.

A finite time is required for the G-M tube to register one pulse, during which time another ionizing event will not be counted. This period is called the "dead time" and is about 200 microseconds. The dead time sets the limit of maximum counting rate at approximately 50,000 c/m or a gamma dose rate of about 20 mrad/hr in the G-M tubes used in the most common survey instruments. The volume and "on-time" of a G-M tube may be altered to produce tubes capable of measuring high dose rates, but with a sacrifice in sensitivity. The output pulses of the G-M tube are generally measured with counting-circuit radiacs such as scalers or count-rate meters.

The response of a G-M tube depends on the voltage at which it operates. If the voltage is low, the tube may be just entering the Geiger region but not at a point where any ionizing event will cause an avalanche of electrons. If the voltage is too high, the tube may tend toward intermittent continuous discharge. Between these two extremes, each G-M tube has what is known as a plateau, or a voltage range of about 150 to 200 volts, where it will respond properly and consistently even with a slight change (25 to 50 volts) in the applied voltage.

Fig. 3.4 is a typical curve of the G-M plateau. By examining the plot of the count rate vs voltage, it can be seen that the G-M tube will start to count at some value, S, above zero. This count rate will increase until the voltage is raised to the threshold value, T. The counting rate will be fairly constant as the voltage is further increased from T to the continuous-discharge value, D. Raising the voltage from point T to D does not change the count rate appreciably. Above Point D, the G-M tube goes into continuous discharge. The region of the curve from T to D is the plateau of the G-M tube. The G-M tube should be operated at a point O above T, one-third the distance of TD.

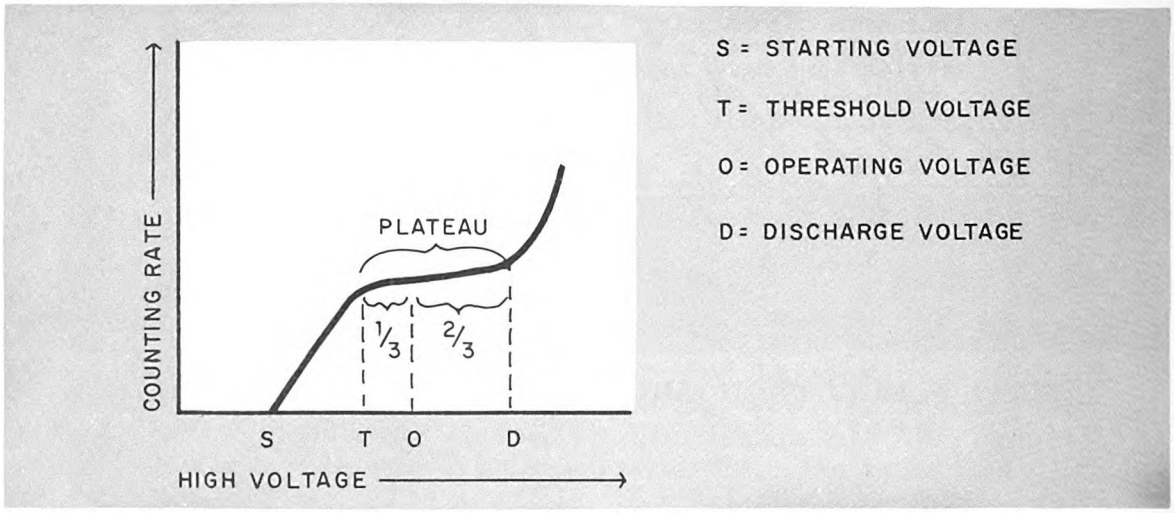

FIG. 3.4 TYPICAL G-M PLATEAU

D. Scintillation Detectors. There are certain substances, such as zinc sulfide, anthracene, and thallium-activated sodium iodide, which emit light (fluoresce) when bombarded by ionizing radiation. The intensity of the light is proportional to the number and energy of the photons or particles striking the scintillation crystal or liquid. A photomultiplier tube is used to measure the light output of the scintillant. For the remainder of this discussion, the scintillant will be considered as a crystal. The output of the photomultiplier tube is electronically amplified to give an indication of the intensity of the radiation. For medium and high intensities of radiation, the photomultiplier is used to produce a current output proportional to the dose rate. For low intensities

of radiation, the photomultiplier tube is used to amplify the individual light pulses from the crystal. A counting circuit is required for recording the output pulses of the photomultiplier. Low-level scintillation monitoring and prospecting radiacs utilize count-rate-meter circuits. By selection of the proper type of crystal and crystal housing and by adjustment of the pulse-height discriminator, a scintillation-type radiac can be made to respond to different types and energies of radiation. Fig. 3.5 is a block diagram of a scintillation-type radiac.

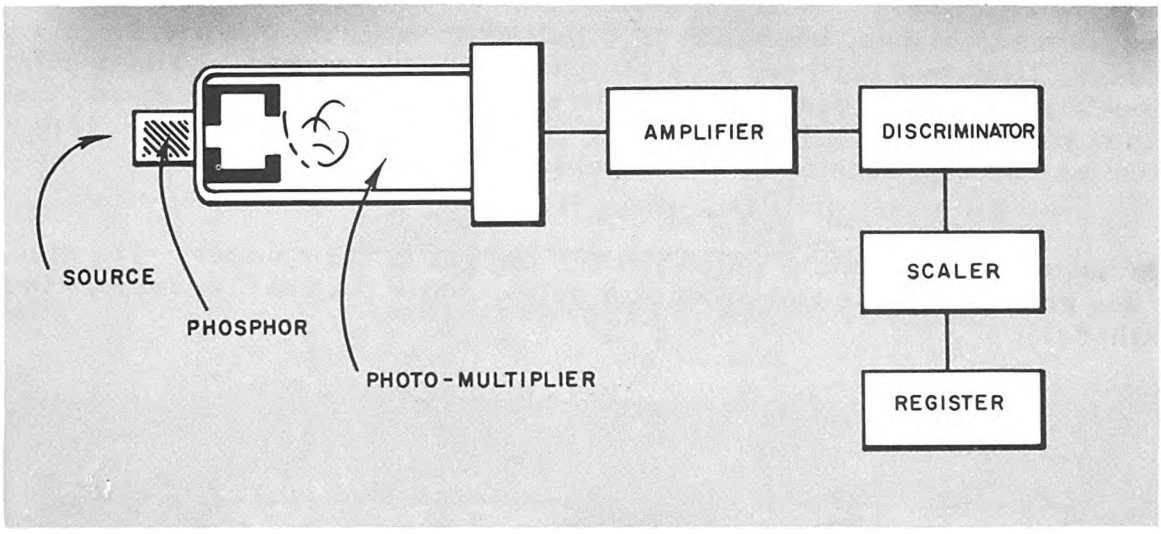

FIG. 3.5 SIMPLIFIED BLOCK DIAGRAM OF SCINTILLATION-TYPE RADIAC

E. Neutron Detectors. Since the neutron is an uncharged particle and cannot be detected directly, neutron detectors must be based upon a measurement of the secondary effects which result from nuclear interactions. For slow-neutron detection, the following two interactions are generally used: (1) absorption of the neutron by the nucleus with emission of a charged particle and (2) absorption of the neutron by the nucleus with the formation of a radionuclide. Fast-neutron detection is generally based upon the principle of elastic scattering, that is, a neutron colliding with a proton and transferring its momentum to the proton. The proton in turn then produces ionization which can be measured.

A common method of detecting slow neutrons is by use of a boron-filled (B^{10}) counter operated in the proportional region. The absorption of a neutron by the B^{10} nucleus results in the emission of an energetic alpha particle which can then be detected by its resultant ionization. Fast neutrons can be detected by slowing them down in a moderator such as paraffin and then counting the thermalized neutron with a boron-filled proportional counter. The boron-filled chamber can be operated in either

the ionization or the proportional region but not in the Geiger region, so that the alpha pulses may be discriminated from the smaller pulses produced by gamma rays. Fig. 3.6 (a) and (b) illustrate the mechanism of slow- and fast-neutron detection with a chamber filled with boron trifluoride gas (BF_3), using a moderator for fast-neutron detection.

In Fig. 3.6 (a), a slow neutron enters the counter and reacts with a boron isotope of mass 10 (B^{10}). (The B^{10} isotope is capable of a slow-neutron capture reaction.) The B^{10} absorbs the neutron in its nucleus, thus raising its mass by one, becoming B^{11}; but B^{11} is unstable and breaks into two pieces, lithium 7 (Li^7) and an alpha particle, He^4 or α^{++}. (The double-plus superscript is used here only to emphasize that it is the doubly charged alpha particle, He^4, which produces the measurable ionization.) This reaction may be represented by the following equation:

$$B^{10} + n^1 \rightarrow B^{11} \rightarrow Li^7 + He^4$$

He^4 is the alpha particle which ionizes the gas in the counter. The electrons go to the anode and produce a pulse, while the positive ions go to the cathode.

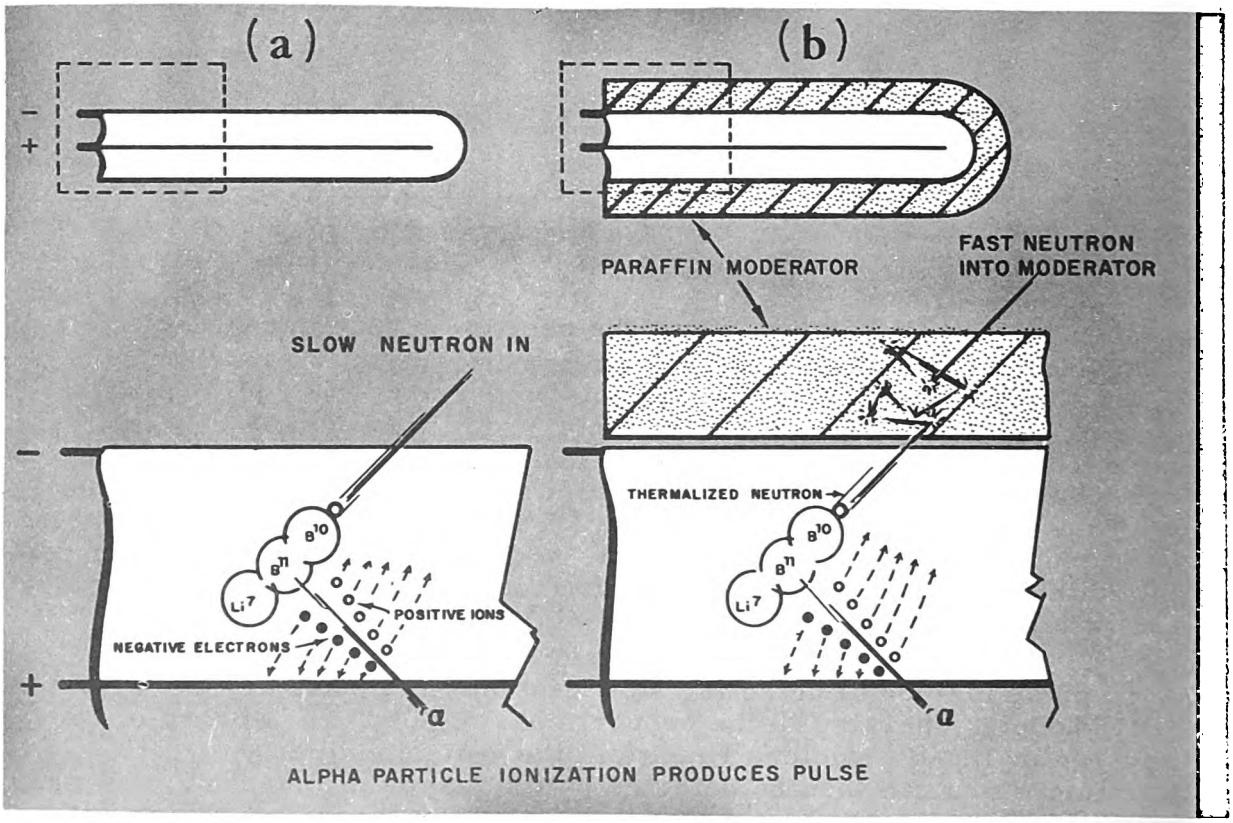

FIG. 3.6 SLOW-AND FAST-NEUTRON DETECTION WITH BORON-FILLED PROPORTIONAL COUNTER

In Fig. 3.6 (b), fast neutrons enter the paraffin moderator and are slowed to thermal speeds. Some of the thermalized neutrons will enter the boron-filled counter resulting in the reaction described above.

Fast neutrons are also detected by measuring the ionization produced by a recoil proton in a polyethylene-lined proportional counter. Fig. 3.7 illustrates the proton recoil reaction.

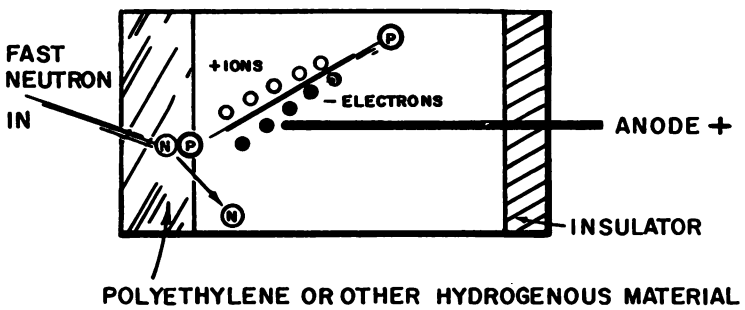

FIG. 3.7 ILLUSTRATION OF FAST-NEUTRON DETECTION BY PROTON RECOIL REACTION

Monitoring of neutron radiation fields is a complex undertaking. In order to make an accurate evaluation of the rem dose rate, the complete energy distribution must be measured. At the present time, however, there are no radiacs (military or commercially-available) capable of measuring the complete neutron spectrum. At best, one may obtain a commercial neutron-monitoring instrument that will detect either slow or fast neutrons but not the intermediate neutron energies.

AEROSOL SAMPLING EQUIPMENT

Aerosol sampling is discussed in Chapter 3, Volume II. The methods and equipment used for collecting and evaluating a sample are set forth in Appendix G, Volume II.

LABORATORY COUNTING EQUIPMENT

Accurate radioanalysis of samples requires the use of scaling or counting equipment. In principle, this counting equipment is identical to portable radiac equipment. A radiation-sensitive detector, such as a Geiger tube or a scintillation counter, is used and a separate electronic counting system records or counts every radiation pulse. Portable radiacs generally indicate the average pulse (count) rate rather than recording each pulse. Fig. 3.8 is a block diagram of a counting system in which a G-M tube is utilized as the radiation detector.

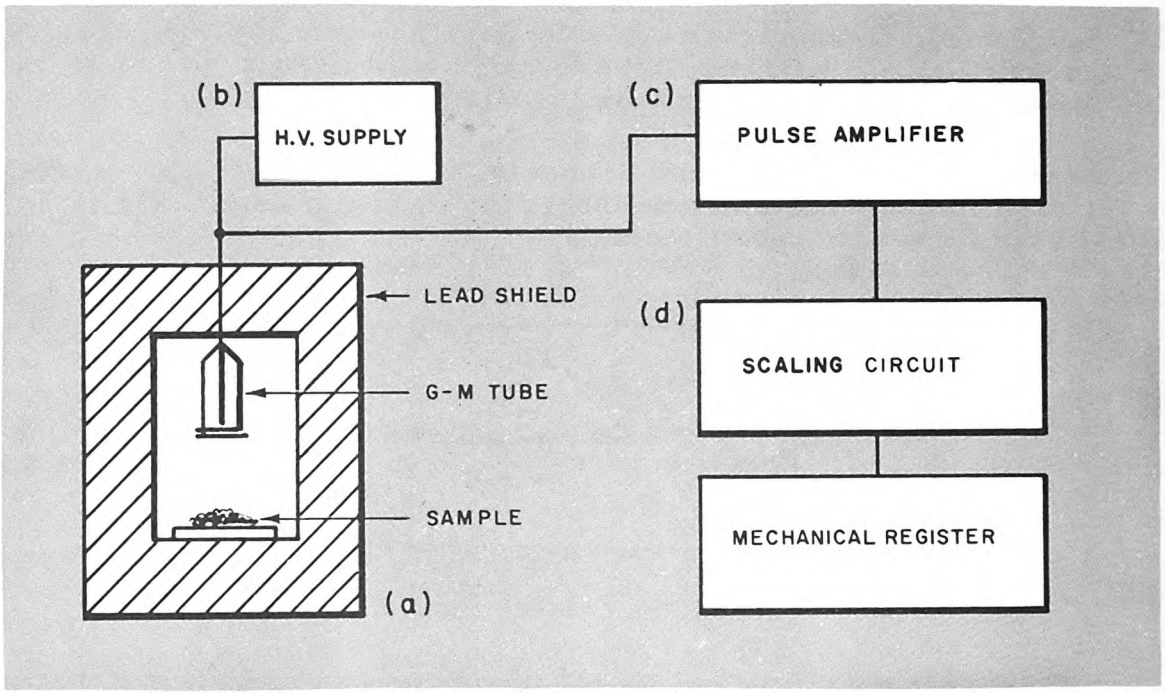

FIG. 3.8 BLOCK DIAGRAM OF G-M COUNTING SYSTEM

The component parts of the G-M counting system are as follows: (a) the G-M tube which produces an electrical discharge for each particle or photon which enters its sensitive volume and causes ionization, (b) a stabilized power supply for the high voltage, usually in the range 800 V to 1500 V, (c) an amplifier to amplify the pulses produced by the G-M tube to the higher level required to operate the scaler, and (d) the scaler and register which record and totalize the pulses received. In addition, there are two further components: a source-mounting to ensure that the radioactive sample preserves a standard geometry with respect to the counter; and a lead shield or "pig" for the G-M tube, source-mounting, and source to be assayed to ensure that the background counts are reduced to a constant minimum value.

In using a G-M counting system, it is necessary to adjust the high voltage so that the tube is operating on the plateau of the counting-rate vs voltage curve. A typical counting-rate vs voltage curve for a G-M tube is shown in Fig. 3.4.

In a well-constructed tube, this flat region of the curve extends over a considerable range of voltages. The tube is operated in this plateau region so that any slight variation of the voltage supply will then have a negligible effect on the recorded counting rate. The G-M tube should be operated on the first one-third of the plateau.

To determine the activity of a sample, two measurements are made: (1) the background counting rate without the radioactive sample and (2) the total counting rate with the radioactive sample. The difference between the two counting rates gives the counting rate due to the sample which in turn is proportional to the amount of radioactive material present. The factor of proportionality is determined by the geometry and the counting efficiency of the counter. Appendix G, Volume II, presents a detailed procedure for determining the plateau of a G-M counting tube, the operating voltages of scintillation and proportional counters, the counter background, and the d/m value of a source, plus certain general rules for counting samples and determining counter efficiencies.

DOSIMETERS. Dosimeters are devices which are worn by individuals to record the accumulated dose of ionizing radiation received by the body. Most dosimeters record only penetrating ionizing radiations although certain types and some specially developed units will record ionizing radiations of low penetrating power. Most dosimeters operate on the principal that ionizing radiations produce chemical or physical changes in matter or result in a current flow due to ionization. The three types generally used are photographic dosimeters (more commonly called film badges), pocket ionization chambers, and glass dosimeters.

A. Photographic Dosimeters (Photodosimeters). Photographic dosimetry or photodosimetry may be described as the measurement of the ionizing radiation dose through the use of special photographic film. Ionizing radiations darken film in much the same manner as does light. The degree of darkening is measured in terms of its optical density. This darkening is proportional to the energy of the radiation and the radiation dose received by the film. The optical density is determined by placing the developed film between a standard light source and a photoelectric cell and measuring the resultant current.

The analysis of the dosimeter film for a radiation dose is made by comparing the unknown film density to a known film density produced by similar radiation of known energy and dose. In other words, a film calibration curve is obtained by exposing the dosimeter film to a given energy of radiation over a range of doses and plotting the resultant film characteristic curve: net density vs dose.

The film packet used for photographic dosimetry is similar to that used for dental X-ray work. It consists of one to three film sheets sealed in a light-tight paper. Each manufacturer lists a packet as a certain type and specifies the component type film to identify the dose range and characteristic response of the packet. For example, the Dupont Company markets a film packet type 544 with component films type 608 and 510. In addition to the film packet type and component films, the manufacturer will also give the emulsion number or batch number of the

component films. All films with the same emulsion number are produced at the same time. The emulsion number is important since the manufacturer is unable to duplicate exactly the chemical properties of the film in new batches.

There are several very important features of photographic dosimeters with which all radiological safety personnel should be familiar. These are:

1. The darkening of film from ionizing radiations depends upon the film type (emulsion), the dose received, and the spectrum (energy) of the incident radiation.

2. The type of holder (filters in the film badge) in which the film packet is held will influence the film response or darkening to various energies of incident radiation.

3. Photographic response of the same type film packet but different emulsion number will vary since the manufacturer is never able to reproduce the exact film emulsion for two batches of film.

4. Heat, pressure, age, and developing procedures affect the film's optical density.

5. Film will darken when exposed to any ionizing radiation whether it is being worn, stored or transported.

Fig. 3.9 demonstrates the spectral (energy) response of a typical dosimeter type film to gamma radiation of various energies. The vertical axis represents the optical density that would be observed for a dose of 1 rad of gamma at the energy listed on the horizontal axis.

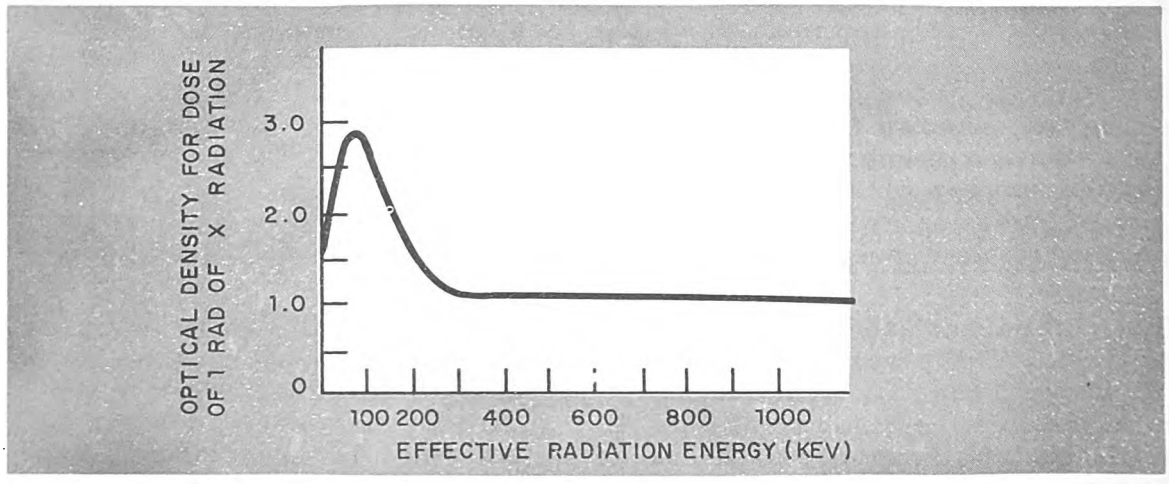

FIG. 3.9 SPECTRAL RESPONSE OF A TYPICAL FILM TO X OR GAMMA RADIATION

Fig. 3.9 shows that a dose of 1 rad of 50 Kev gamma radiation will produce an optical density of 2.8, while a dose of 1 rad of 500 Kev gamma radiation produces a density of 1.0. Thus, to compute the dose received when the optical density is known, the response of the film to the incident radiation must be known. When the film packet is placed in a holder and/or is partially covered with filters, the response of the film under the filters to various energies of incident radiation must be determined. This can be accomplished by exposing the film in the holder to a known dose of a certain radiation energy.

Table A-1 of Appendix A of this volume provides energy and dose rate information for various isotopes.

Once the characteristic response curve of a film type to a certain radiation energy has been determined, any change in emulsion numbers generally does not affect the response curve shape but may shift the position of the entire calibration curve. This may be compensated for by making a new series of controlled exposures and noting the shift in optical density for a known dose.

Since pressure on a film packet will alter its response, caution must be exercised to prevent any bending of, or pressure on (including writing), the film packet. (A fountain pen or a grease pencil - - not a ball point pen--with light pressure may be used to place identifying marks on a film packet.)

To compensate for the effects on film from age, heat, variation in developing procedures, developing solutions, and radiation received in storage, several control films (blank or unexposed and standard or exposed to known doses) are developed with each group of processed film. The optical density noted on unexposed films is subtracted from the gross optical density of exposed films. In this manner, any change in optical density occurring during storage or processing is removed from the optical density reading. All calibration curves are constructed using the net optical density. Net optical density equals the gross optical density observed minus the optical density of the control film.

Film will darken from any exposure to ionizing radiation. Therefore, when not being worn, all films should be stored in a radiation-free area or in a shielded container along with several control films.

Since film response varies with the energy of the incident radiation as well as the dose received, all film calibration should be done against a source of the same energy as that to which the film will be exposed. The gamma radiation spectrum encountered from fission products in weapons tests is a mixed spectrum with an average energy of 0.7 Mev. Calibration of film for fission product dosimetry may be accomplished with radium which has a mixed energy spectrum with an average energy of

about 0.8 Mev. The beta calibration can be made with normal uranium plaques or specially prepared Sr^{90}-Y^{90} plaques.

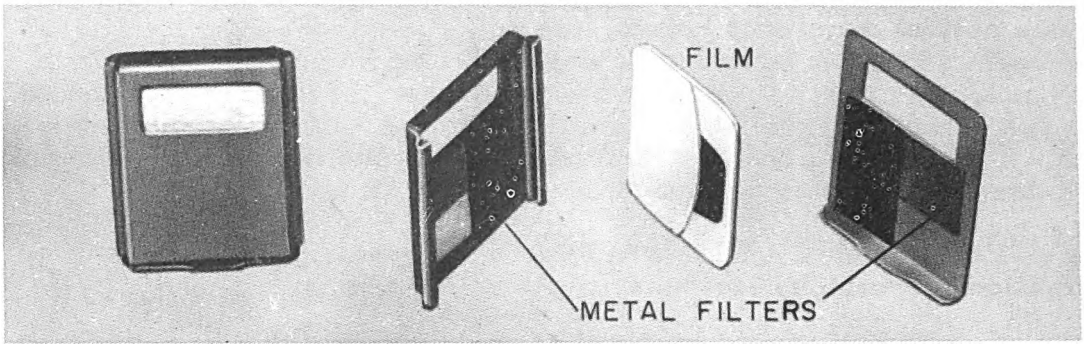

FIG. 3.10 LABORATORY-TYPE FILM BADGE WITH DUPONT 508 AND 510 FILM

Fig. 3.10 shows a laboratory-type film badge. The metal holder in the badge is made of 0.040 in. aluminum with 0.027 in. lead and 0.015 in. cadmium filters.

These filters produce different densities of film darkening depending upon the radiation spectrum. Reference to various energy calibration curves makes possible the dose computation. Film packets with various film types may be used to obtain the dose range and spectral response required.

A film badge designed for field operations is shown in Fig. 3.11. The film packet has a 0.027 in. lead shield and is serially prenumbered by the manufacturer. The lead shield is used to differentiate between hard and soft gamma radiation. The serial number placed on each film packet can be seen on the developed film sheet. The film packet is encased in a watertight plastic container with an eyelet for wearing with a "dog tag" chain.

For further information on processing, developing, and evaluating, the reader should refer to NBS Handbook 57, Photographic Dosimetry of X and Gamma Rays, or to the booklet Evaluating Films for Monitoring X Rays and Gamma Rays, published by the American Standards Association, 70 East 45th St., New York, New York.

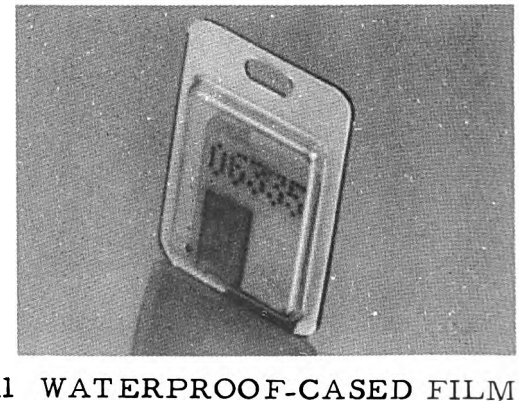

FIG. 3.11 WATERPROOF-CASED FILM BADGE FOR FIELD OPERATIONS

B. Pocket Ionization Chambers. Many radiac instruments indicate only the dose rate at a particular time and location, but the problem of estimating accurately the total dose received by a person in varying radiation fields is difficult to compute from radiac dose rate readings. The film badge previously discussed records the total dose received, but this information is not available until processing of the film is completed.

To obtain the total dose received by a person at any time, pocket ionization chambers are used. There are two types of pocket ionization chambers: self-reading and non-self-reading.

1. Self-reading. The self-reading pocket ionization chamber is a quartz electroscope with a built-in scale. When the electroscope is charged, a movable metal-coated quartz fiber separates from a fixed metal leaf. The movable quartz fiber is so constructed and located that its position may be observed in relation to a calibrated scale. When originally charged, the separation from the fixed leaf is adjusted so that the movable fiber is at the 0 mark on the scale. As ionizing radiations are absorbed by the chamber, the original charge or potential placed on the electroscope is reduced, and the movable fiber approaches the fixed fiber. This movement is observed through a lens system in relation to the calibrated scale. Thus, the total dose received up to any moment may be determined by observing the movable fiber's position in relation to the calibrated scale. The self-reading dosimeters are supplied in many dose ranges, such as 0-200 mr, 0-1 r, 0-5 r, 0-100 r, etc. Most dosimeters are designed to read only penetrating X or gamma radiations. Each dosimeter should be calibrated for the energy range to which it will be exposed. Fig. 3.12 illustrates a self-reading pocket dosimeter.

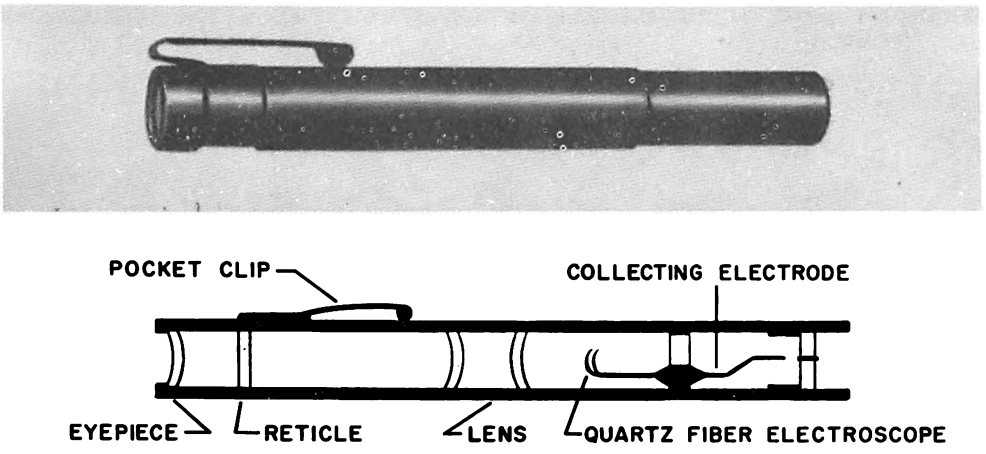

FIG. 3.12 SELF-READING POCKET IONIZATION CHAMBER

2. Non-self-reading. The non-self-reading pocket dosimeter is a more rugged instrument but serves the same purpose as the self-reading dosimeter. It is similar in construction to a condenser, having a central electrode which is insulated from the chamber wall. A charge is placed on the center electrode by a charging device (often called a minometer). This charging device contains a power supply, a calibrated scale observed through a lens system, and a means of varying the charge. When the dosimeter is charged, a movable fiber in the charging unit is placed on 0. When read, the dosimeter is inserted into the charger, and the position of the movable fiber is observed in relation to the calibrated scale. The position of the movable fiber in relation to the calibrated scale indicates the dose received by the dosimeter. (CAUTION: Always read the dosimeter on the same charger used to charge the dosimeter.) Fig. 3.13 illustrates the non-self-reading dosimeter.

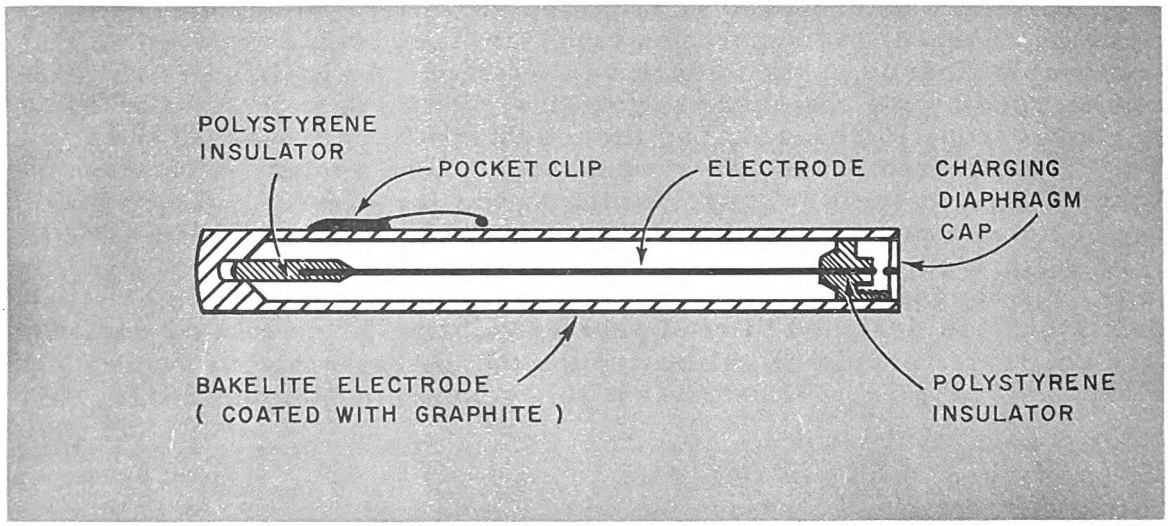

FIG. 3.13 NON-SELF-READING POCKET IONIZATION CHAMBER

Most of the pocket ionization chambers in use today are designed to measure X and gamma radiation, but by proper design of chamber wall or gas-filling material, pocket ionization chambers may be used to measure other types of ionizing radiation. The thermal neutron pocket ionization chamber utilizes a boron-lined wall to make use of the $B^{10} + n \rightarrow B^{11} \rightarrow Li^{7} + He^{4}$ capture reaction. The alpha particle (He^{4}) produces the ionization in the chamber. The reaction is identical to the reaction in thermal neutron monitoring radiacs using boron-lined or boron-gas-filled chambers.

Pocket ionization chambers are delicate instruments and should be kept clean, since dirt on the insulator will increase charge leakage. If these instruments are dropped, they may be discharged. Pocket ionization chambers should be used in pairs whenever possible, and the lower reading is the more probable dose received by the wearer.

C. Glass Dosimeters. The film badge previously discussed indicates the total dose received by personnel once the processing is completed, but once processed, the film can never be used again; therefore, records must be kept if the total exposure from several radiation exposures is to be determined. The pocket dosimeter, although reusable, produces the same problem in that it must be recharged, thus requiring that individual readings be recorded if a total dose is to be determined. To overcome this problem, the U. S. Navy has developed the DT-60 Personnel Dosimeter, which is a glass device. Unfortunately, the minimum accumulated dose which may be determined is about 25 r.

The DT-60 is classed as a casualty personnel dosimeter because it is designed to measure an accumulated gamma dose from a minimum of 25 r up to 600 r when used with the CP-95/PD reader. The dosimeter consists of special phosphate glass, housed in a moisture-proof bakelite case. Gamma radiation changes the amount of orange fluorescence of the phosphate glass when exposed to ultraviolet light. This change in orange fluorescence, which is proportional to the accumulated dose, must be read on a calibrated reader. The dosimeter is about the size of a pocket watch, weighs less than an ounce and is extremely durable. This dosimeter is linear up to at least 600 r, cumulative and independent of dose rate. Its response is independent of the energy of the incident gamma radiation within $\pm$ 20% over the range 80 Kev to 2 Mev. The dose indication is stable with time, and the dosimeter may be read repeatedly. Fig. 3.14 illustrates the DT-60 Personnel Dosimeter.

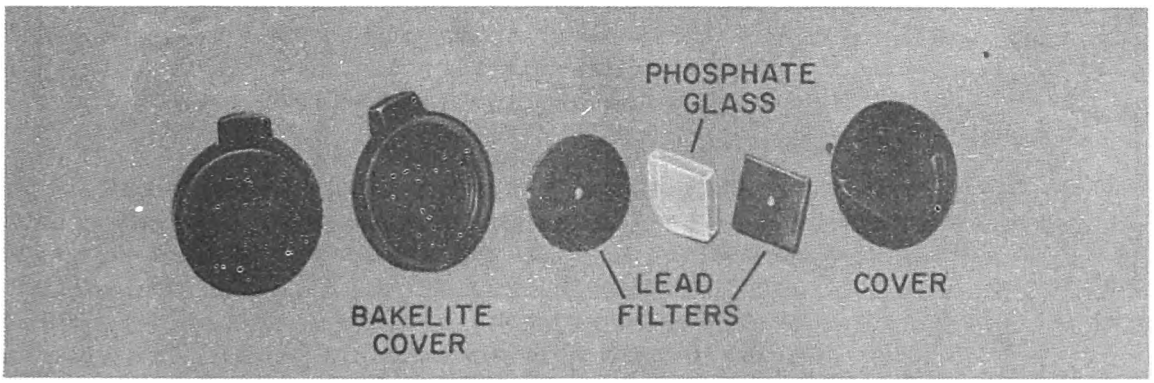

FIG. 3.14 DT-60/PD PERSONNEL DOSIMETER

CALIBRATION OF RADIAC INSTRUMENTS

Many types of radiation detection instruments are currently being used for monitoring purposes. Manufacturers of these instruments advertise certain qualities and attempt to guarantee their products, but through use, abuse, age, and faulty parts, equipment may not respond to design specifications although the equipment still responds qualitatively to radiation. Therefore, it is extremely important that the accuracy of these radiacs be maintained by frequent calibration. This fact cannot be over-emphasized, for in many cases a serious injury or fatal accident may occur if a monitoring radiac is far out of calibration.

A. Calibration Sources. The radiac instrument to be calibrated will determine the calibration source and its size. The energy spectrum of the calibration source will depend on the isotope selected. Generally, the calibration source selected should be compatible with the intended use of the monitoring radiac. Although radiacs are designed to produce a flat response over a fairly wide radiation spectrum, certain instruments vary sharply in their energy response, especially below 200 Kev and above 5 Mev. If possible, the rule to follow is to calibrate the radiac with the same energy and type of radiation as that which the instrument will be required to measure. Information on three sources commonly used for calibration is presented in Table 3.1.

Table 3.1

Dose Rate from 1 Curie of Co^{60}, Cs^{137}, and Ra^{226}

Isotope	Half-Life	r/hr at 1 ft	r/hr at 1 meter
Co^{60}	5.2 yr	14.3	1.32
Cs^{137}	30 yr	3.83	.356
Ra^{226} in equilibrium with decay products	1620 yr	Filter Thuringian Glass 0.5 mm Pt-Ir 1.0 mm Pt-Ir Each mm of lucite reduces the gamma output by 0.35%.	0.93 0.84 0.78

Additional information concerning dose rate output and energy of commonly used radioisotopes will be found in Table A-1 of Appendix A.

Gamma calibrating sources should be calibrated by NBS (National Bureau of Standards) or against certified NBS sources of the same type or at least of similar spectrum. Victoreen r-chambers or other comparable thimble chambers calibrated by NBS or calibrated against an NBS source can be used to calibrate a source's output with an accuracy of ± 3%. The ideal source-to-instrument geometry is that which produces minimum scatter and uniform radiation flux through the radiation detection element of the radiac. This means the source should be suspended in the middle of a room of such dimensions that scatter radiation will be minimized. However, in the practical case, the calibrating source will be housed in a lead shield with a removable shield aperture to produce a cone of radiation as in the Radiac Calibrator Set, AN/UDM-1. A calibration curve of dose rate vs distance from center of the source should be a part of every radiac calibration source to facilitate calibration. It should be mentioned that the inverse-square law does not always hold due to scatter and absorption from the source holder, mounting, physical layout of the room, etc., so thimble chambers should be used to check all points in question for the maximum accuracy. This is especially true for film badge calibration. The half-life of each calibration isotope must be considered before calibration is started, particularly when calculated dose rates are to be used rather than thimble chamber readings. Dose rates must be corrected for losses due to decay.

Beta calibrating sources may be infinitely thick (with respect to maximum range of the beta particle) plaques containing a homogeneous distribution of the beta emitter in question. Normal uranium plaques are very often used as beta standards. The normal uranium beta plaque has a contact beta dose rate of around 240 mrad/hr as measured by several investigators through extrapolation chamber techniques. The rad output of various other beta plaques can be measured with an extrapolation chamber or by precise counting techniques where very low dose rates are required.

Once the beta dose rate from a source is known, the particular radiac may be calibrated for that energy of beta radiation. Since the hazard from external beta radiations is to the skin, the dose rate to the skin is generally desired. This dose rate may be expressed as the mrad/hr at the basal layer of the epidermis when in contact with the source.

The calibration of a radiac for beta response is dependent upon: (a) the energy spectrum of the beta emitters, (b) the size and shape of the surface, (c) the amount and distribution of the radioactive substance on the surface, (d) self-absorption and absorption by the material on which the source is located due to penetration of the beta emitter into it, (e) backscatter and (f) the point at which the measurement is made. For the above reasons it is difficult to express a simple beta calibration for a particular instrument.

To demonstrate the above points, Figures 3.15 and 3.16* showing the relationship between the ratio of contact dose rate at the basal layer of the epidermis to survey instrument readings as a function of source-to-survey-instrument distance and the energy of the beta emitter are presented. It will be noted for either the ion chamber or G-M type radiac a correction factor of approximately 8 must be applied to the meter reading for a 1 inch source-to-chamber measurement, increasing as the distance from the source increases. (Distance is measured perpendicularly from the edge of the source plane to the nearest projection of the instrument, rubber tips on the CDV-700 not considered. The edge of the instrument or axis of G-M tube parallel to an edge of the source.)

Alpha calibrating sources consist of an alpha emitter deposited on a planchet and calibrated by NBS or against an NBS standard. Standard alpha sources can be purchased from NBS or from commercial establishments.

Most standard neutron sources are based on the α,n reaction of Be with the α particle supplied by a long-lived radioisotope. The Ra-Be neutron source is made by compressing a mixture of $RaBr_2$ powder and powdered Be to maximum density. These sources produce an emission rate, $\underline{Q}$, of about 10^7 n/sec/gm of Ra. Absolute determination of $\underline{Q}$ for a standard source is a difficult task; up to the present time, most absolute calibrations have been made with an accuracy of ± 5%.

B. Calibration of G-M Radiacs. (Consult manufacturer's instruction books, if available.) Although there are many models of G-M radiacs currently in use, basically there is no difference in these instruments except in outward appearance; the operation and calibration are the same for each. G-M radiacs, with the G-M tube mounted in the probe, act primarily as a contamination detection instrument. Their purpose is to determine if certain types of radiation are or are not present, indicating a general order of magnitude but not a true dose rate. True dose rate can be determined only if the instrument is calibrated against the same energy spectrum.

For gamma calibration, a dose rate is determined by calculation or preferably by thimble chamber measurement at a point in space in the radiation field of the calibration source. The G-M tube is then placed at this exact location and the meter reading noted. Sensitivity adjustments may have to be made to the electronic circuits; if so, they should be accomplished using rad-safe procedures to minimize the radiation dose received by personnel doing the calibration (see Chapter 2, Volume II). A common practice is to

* U. S. Atomic Energy Commission Document NYO-4698 of 1956.

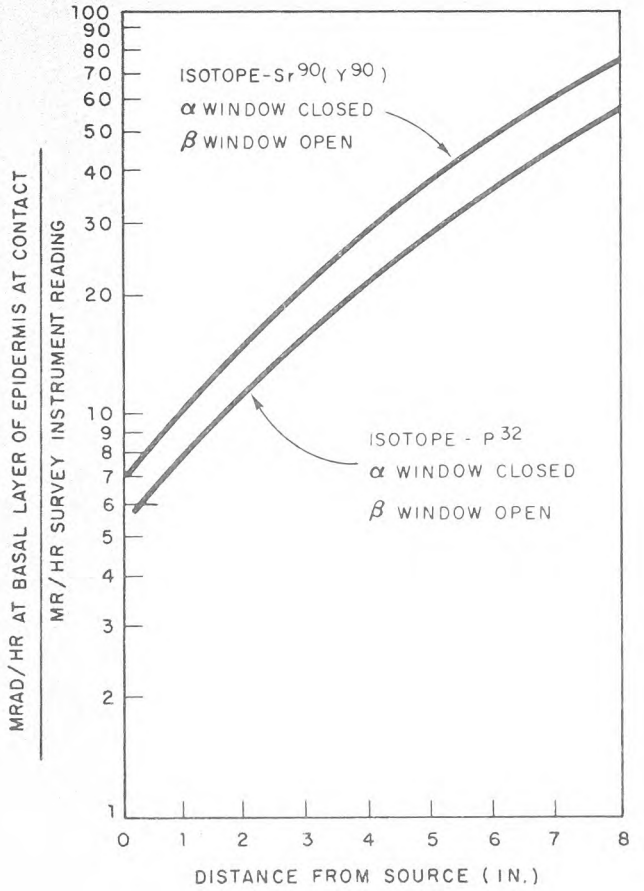

FIG. 3.15 RATIO OF CONTACT DOSE RATE AT THE BASAL LAYER OF THE EPIDERMIS TO SURVEY INSTRUMENT READING AS A FUNCTION OF SOURCE-TO-SURVEY-INSTRUMENT DISTANCE.

Type Instruments: SIC-17C, SIC-17D (low and high range JUNO) Ion Chamber Type.

Sources: Plane, thin, 6 in. x 6 in. square, backing of thick plexiglas.

Error: These are composite curves based on three SIC-17C and four SIC-17D instruments. This small sampling indicates that a departure of ± 10% might easily be expected for any given instrument.

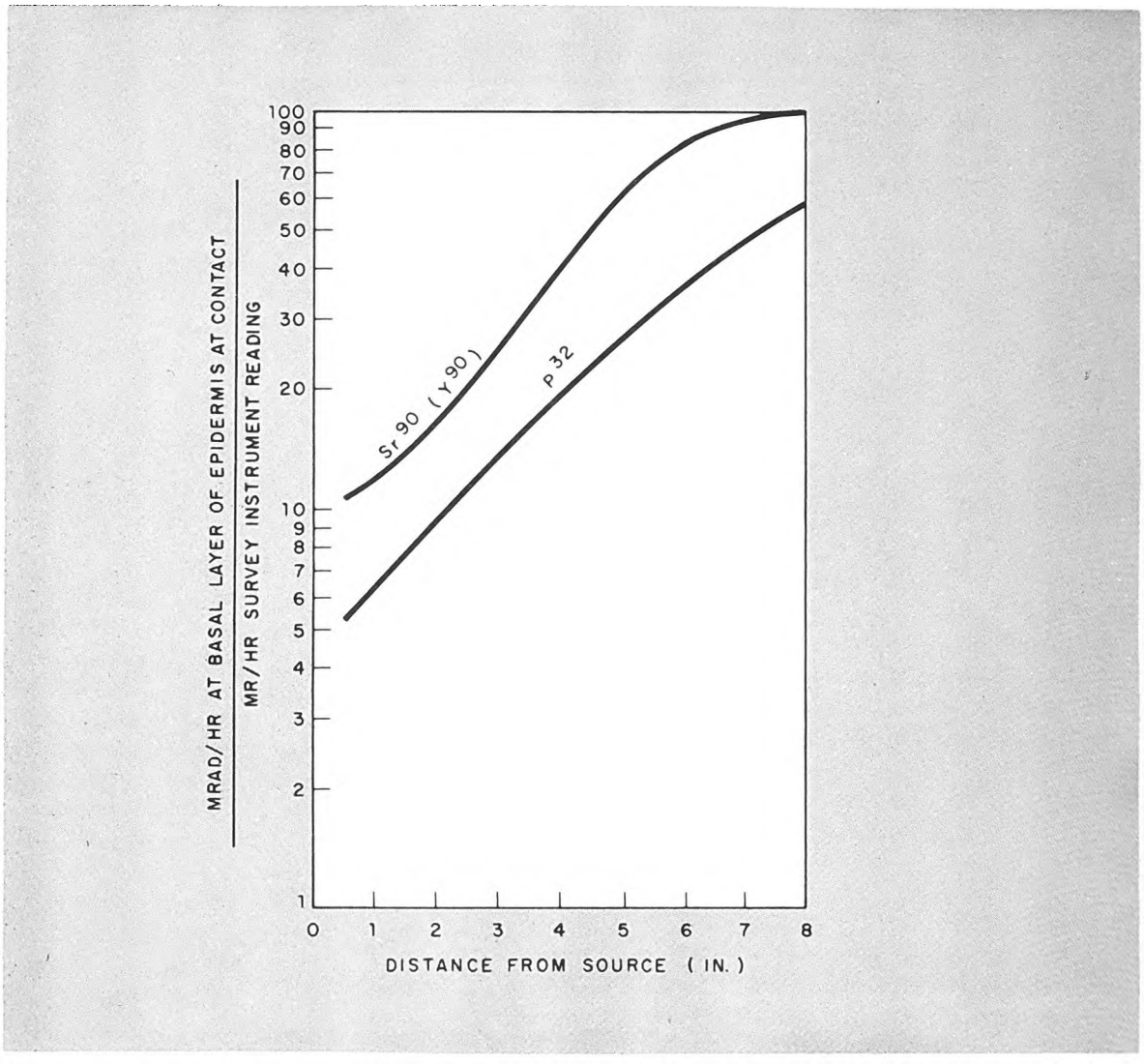

FIG. 3.16 RATIO OF CONTACT DOSE RATE AT THE BASAL LAYER OF THE EPIDERMIS TO SURVEY INSTRUMENT READING AS A FUNCTION OF SOURCE-TO-SURVEY-INSTRUMENT DISTANCE.

Type Instrument: CDV-700 G-M Type Radiac.

Sources: Plane, thin, 6 in. x 6 in. square, backing of thick plexiglas.

Error: These are composite curves based on three instruments. This small sampling indicates that a departure of $\pm$ 20% might easily be expected for any given instrument.

expose the source, observe the meter reading by optical means, and shield the source before making the necessary adjustments. This procedure is repeated until the proper adjustment of circuits is obtained. Calibration should be accomplished with the probe in the same general relation to the source as it will be when monitoring. (This will be perpendicular to the source in most cases.) Calibration checks should be made on each scale of the meter at 20, 50, and 80% of full scale. When in use, the instrument should occasionally be checked at a point on each scale to verify the calibration. Background should be subtracted from the low range before plotting the calibration curve.

G-M type survey instruments generally are not calibrated against beta radiation because substances emit beta particles with a distribution of energies. The lower energy particles will not penetrate the detector tube. The fraction that does penetrate the tube depends upon the energy distribution which in turn is characteristic of the isotope being measured. Therefore, in order to obtain an accurate measure of beta radiation, the G-M survey meter must be calibrated against the isotope which it is being used to measure. If possible, the same source-to-detector geometry should be maintained. The reading obtained when the beta shield is open will generally be several times the gamma radiation reading. It should be noted, however, that the beta reading bears no relation to roentgens. Where a quantitative measurement of beta radiation is necessary, laboratory instruments should be used or a direct comparison of the monitoring radiac to the proper beta standard should be made.

C. Calibration of Ion Chamber Radiacs. The calibration of ion chamber survey meters is similar to that for the G-M type in most respects. The AN/PDR-T1B type ion chamber has a total of five scales: 0-5, 0-50, 0-500, 0-5,000, and 0-50,000 mr/hr and will be used to illustrate the typical ion chamber radiac. The procedure used is the same as that for G-M survey meters except that a stronger source is required.

Since most radiacs measure the actual dose rate within ± 20%, the calibration of radiacs for radiological safety monitoring purposes need not be as precise as for technical experimental measurements. Therefore, a radiac calibration check generally consists of determining a correction factor for each scale. The check point is usually taken at half-scale. For the T1B, the check points would be 2.5, 25, 250, 2500, and 25,000 mr/hr. Table 3.2 lists the radiation levels at various distances from a 500 mg Ra source and typical instrument measurements. The correction factor is obtained by dividing the calculated dose rate by the measured dose rate. If the correction factor is less than 0.8 or greater than 1.2, the instrument should be rejected and given a complete overhaul.

Table 3.2

Dose Rate vs Distance From 500 mg Ra Source

Calculated Dose Rate (mr/hr)	Distance (cm)	Measured Dose Rate (mr/hr)	Correction Factor
25,000	13.0	22,000	1.14
2,500	41.2	2,300	1.08
250	130	300	0.84
25	412	21	1.19
2.5	1304	3	0.84

(Meter Reading) x (Correction Factor) = Dose Rate

Distance measurements must be made from the center of the sensitive volume of the instrument to the source. In the case of the T1B, this is about 3 inches from the front edge of the instrument. The scale selector switch on the T1B should be placed on the SET position and the instrument given 15 minutes to warm up before readings are taken. Ionization chamber instruments hold their calibration well and do not require recalibration after short periods of use, as do the G-M type instruments. A new instrument should be calibrated when received and periodic calibration checks should be made thereafter. If possible, calibration of the instrument should be accomplished with the chamber in the same position with respect to the source as it will be when used in monitoring.

D. Calibration of Alpha Radiacs. The calibration of the alpha proportional counter is a more complex operation than other types as it requires very accurate adjustments of the batteries and circuit components. The "Pee Wee" proportional alpha counter described in App. B, Vol. II, utilizes probes of several shapes and sizes, depending on the area or surface to be surveyed. The reading of the meter will be greatly affected by the type of probe used and by the energy of alpha particles measured. The distance of the probe from the contaminated surface will also have a great effect, since alpha particles have a range of only a few inches in air.

Before monitoring for alpha contamination, the instrument should be checked for efficiency by comparing it with an alpha standard. Generally, the efficiency should be electronically adjusted to read out a 50% geometry. Alpha standards should always be used before and during monitoring to check calibration. Laboratory instruments such as gas-flow alpha counters should be used where quantitative measurements must be made.

E. Calibration for Final, Standard and Operational Clearances.

Final, standard, and operational clearance gamma dose rate levels should be made with conventional-type radiacs which may be calibrated in the previously described manner. The contamination levels should be measured with radiacs calibrated against contamination standards with the same radiation spectrum and intensity level in question. For example, aged fission product activity can be used in preparing fission product contamination standards to be used to calibrate radiacs by fixing the activity to a metal backing or by making a homogeneous fission product activity plaque.

(PORACC)

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GLOSSARY

ABSORBED DOSE: The energy that ionizing radiation delivers per gram of material absorbing it. The unit is the rad (100 ergs per gram). See Dose.

ABSORPTION: The process by which the number of particles or quanta in a stream of radiation is reduced as it passes through some medium. The absorbed radiation may be transformed into other radiation or energy by interaction with the electrons or nuclei of the atoms upon which it impinges.

NOTE: In the above sense this term is used interchangeably with attenuation. More specifically, absorption refers to processes by which the radiation disappears or is transformed, and not merely scattered.

ABSORPTION COEFFICIENT: A number characterizing the ability of a given material to absorb radiations of a specified energy. The linear absorption coefficient expresses this ability per unit thickness and is stated in units of reciprocal length (or thickness). The mass absorption coefficient is equal to the linear absorption coefficient divided by the density of the absorbing material; it is a measure of the absorption ability per unit mass.

AEROSOL: Suspension of particles in a gaseous medium, usually air. The particulate constituents are dust, fumes, smoke and mists, ranging in size from below 0.1 micron to 8000 microns.

AIR BURST: The explosion of a nuclear weapon at such a height that the expanding ball of fire does not touch the earth's surface when the luminosity is a maximum (in the second pulse). A typical air burst is one for which the height of burst is such as may be expected to cause maximum blast destruction in an average city.

ALPHA PARTICLE: A particle emitted spontaneously from the nuclei of some radioactive elements. It is identical with a helium nucleus, having a mass of four units and an electric charge of two positive units. See Radioactivity.

ATOM: The smallest (or ultimate) particle of an element that still retains the characteristics of that element. Every atom consists of a positively charged central nucleus, which carries nearly all the mass of the atom, surrounded by a number of negatively charged electrons, so that the whole system is electrically neutral. See Element, Electron, and Nucleus.

ATOMIC CLOUD: An all-inclusive term for the mixture of hot gases, smoke, dust, and other particulate matter from the bomb itself and from the environment, which is carried aloft in conjunction with the rising ball of fire produced by the detonation of a nuclear (or atomic) weapon.

ATOMIC NUMBER: See Nucleus.

ATOMIC WEIGHT: The relative weight of an atom of the given element. As a basis of reference, the atomic weight of oxygen is taken to be exactly 16; the atomic weight of hydrogen (the lightest element) is then 1.008. Hence, the atomic weight of any element is approximately the weight of an atom of that element relative to the weight of a hydrogen atom.

ATTENUATION: In radiation theory, the reduction in the flux density, or power per unit area, with distance from the source; it may be due to absorption, to scattering, or to both processes. In nuclear physics, the reduction in the intensity of radiation upon passage through matter; in general, it is due to a combination of scattering and absorption.

AVALANCHE: The multiplicative process in which a single charged particle accelerated by a strong electric field produces additional charged particles through collison with neutral gas molecules. This cumulative increase of ions is also known as Townsend ionization or Townsend avalanche.

BACKGROUND COUNTING RATE: That undesired radiation component detected by instruments due to cosmic rays, to radioactive materials in the vicinity, and to a slight radioactive contamination of the materials of which the instruments are made.

BACKGROUND RADIATION: Ionizing radiations arising from within the body and from the surroundings to which individuals are always exposed. The main sources of the natural background radiation are potassium-40 in the body, potassium-40 and thorium, uranium, and their decay products (including radium) present in rocks, and cosmic rays.

BALL OF FIRE (OR FIREBALL): The luminous sphere of hot gases which forms a few millionths of a second after a nuclear (or atomic) explosion and immediately starts to expand and cool. The exterior of the ball of fire is initially sharply defined by the luminous shock front (in air) and later by the limits of the hot gases themselves.

BASE SURGE: A cloud which rolls outward from the bottom of the column produced by a sub-surface explosion. For underwater bursts the surge is, in effect, a cloud of liquid (water) droplets with the property of flowing almost as if it were a homogeneous fluid. For sub-surface land bursts the surge is made up of small solid particles but it still behaves like a fluid. A soft earth medium favors base surge formation in an underground burst.

BETA PARTICLE: A charged particle of very small mass emitted spontaneously from the nuclei of certain radioactive elements. Most (if not all) of the fission fragments emit (negative) beta particles. Physically, the beta particle is identical with an electron moving at high velocity. See Electron, Radioactivity.

BINDING ENERGY: The energy required to remove a particle from its position in the atomic nucleus, or an electron from its orbit. The total binding energy of an atom is the energy represented by the difference between the sum of the masses of the component parts and the actual mass of the atom.

BIOLOGICAL HALF-LIFE: See Half-Life.

BONE SEEKER: Any element or ion which migrates in vivo preferentially into bone.

BREMSSTRAHLUNG: Electromagnetic radiation (X rays) produced by the deceleration of charged particles (usually electrons) passing through the electromagnetic field of nuclei.

BUILD-UP FACTOR: In gamma-ray shielding theory, the ratio of (1) the actual radiation dose rate at a point beyond the shield to (2) the dose rate calculated by assuming that no photons are scattered into the detector by the shield:

$$\text{(Build-Up Factor)}\quad B(x) = \frac{I}{I_o e^{-\mu x}}$$

$$\text{so that}\quad I = B(x)\, I_o e^{-\mu x}$$

where I = actual dose rate at some point

I_o = dose rate at the same point with no shield present

μ = total attenuation coefficient

x = thickness of shield.

For lead shields, $B(x)$ varies from 1.0 to about 4 as x varies from 0 to 16 cm. To the first approximation, $B(x)$ may be represented by the numerical value of $(1 + \mu x)$.

BURST: Explosion or detonation. See Air Burst, Surface Burst Underground Burst, Underwater Burst.

CALIBRATION: The determination of the accuracy of a measuring instrument; also, the determination of the necessary correction factors to be applied to the instrument readings.

CAPTURE, RADIATIVE: The process by which a nucleus captures an incident particle and loses its excitation energy immediately by the emission of gamma radiation.

CHAIN REACTION: Any chemical or nuclear process in which some of the products of the process, or energy released by the process, are instrumental in the continuation or magnification of the process. Nuclear fission can be such a process.

CHANGE HOUSE OR CHANGE STATION: See Personnel Decontamination Center.

CHEMICAL DOSIMETER: A self-indicating device for determining total (or accumulated) radiation exposure dose based on color changes accompanying chemical reactions induced by the radiation.

COLLISION, ELASTIC: Collision in which kinetic energy and momentum of each colliding system are conserved.

COLLISION, INELASTIC: Collision in which at least one system gains internal excitation energy at the expense of the total kinetic energy.

COMPOUND: A pure chemical substance composed of two or more elements combined in a fixed and definite proportion by weight. Its properties, on the whole, are different from those which their constituents had as elementary substances.

COMPTON EFFECT: An absorption effect observed for X and gamma radiation in which the incident photon interacts with an orbital electron of the absorber atom to produce a recoil electron and a photon of energy less than the incident photon.

CONTACT HAZARD, RADIATION OR CONTAMINATION: Radiation hazard resulting from direct bodily contact with contaminants, or from prolonged contact with a sealed source of gamma radiation.

CONTAMINATION, RADIOACTIVE: Deposition of radioactive material in any place where it is not desired, and particularly in any place where its presence may be harmful. The harm may arise from invalidating the results of an experiment or a procedure, or in actually being a source of danger to personnel.

CONTROL CENTER: A station usually at the perimeter of a radiation or contamination zone to control excessive exposure to ionizing radiation through issue of protective equipment and radiological safety instructions and to control the spread of contamination through decontamination. Control Center is often used synonymously for Change Station or Decontamination Center.

COUNT RATE METER: A device which gives a continuous indication of the average rate of ionizing events.

COUNTING RATE: The average rate, as a time function, at which ionizing events are indicated by an electronic circuit.

CRITICAL MASS: The minimum mass of a fissionable material that will just maintain a fission chain reaction under precisely specified conditions, such as the nature of the material and its purity, the nature and thickness of the tamper (or neutron reflector), the density (or compression), and the physical shape (or geometry). For an explosion to occur, the system must be supercritical, i.e., the mass of material must exceed the critical mass under the existing conditions. See Supercritical.

CUMULATIVE DOSE (RADIATION): The total dose resulting from repeated exposures to radiation of the same region, or of the whole body.

CURIE: A unit of radioactivity; it is the quantity of any radioactive species in which 3.7×10^{10} nuclear disintegrations occur per second. The "gamma curie" is sometimes defined correspondingly as the quantity of material which emits 3.7×10^{10} gamma rays per second.

DECAY (OR RADIOACTIVE DECAY): The decrease in activity of any radioactive material with the passage of time, due to the spontaneous emission from the atomic nuclei of either alpha or beta particles, usually accompanied by gamma radiation. See Half-Life, and Radioactivity.

DECAY CURVE: The representation by means of a graph of the decrease of radioactivity with respect to time.

DECONTAMINATION: The reduction or removal of contaminating radioactive material from a structure, area, object, or person. Decontamination may be accomplished by (1) treating the surface so as to remove or decrease the contamination; (2) letting the material stand so that the radioactivity is decreased as a result of natural decay; and (3) covering the contamination so as to attenuate the radiation emitted. Radioactive material removed in process (1) must be disposed of by burial on land or at sea or in some other suitable way.

DECONTAMINATION FACTOR: The ratio between the amount of undesired radioactive material initially present to the amount remaining after a suitable processing step has been completed. Decontamination factors may refer to the reduction of some particular type of radiation, or of a gross measurable radioactivity.

DENSITOMETER: Instrument for measuring optical density.

DENSITY (PHOTOGRAPHIC): Density is a measure of the degree of darkening of photographic film.

DEPTH DOSE: The absorbed dose delivered at a particular depth (usually 10 cm) beneath the surface of the body. For any radiation it is usually expressed as percentage of the absorbed dose at the surface. For X or gamma rays it may be expressed as rads per roentgen of exposure. It may also be expressed directly in rads.

DISINTEGRATION, NUCLEAR: A spontaneous nuclear transformation (radioactivity) characterized by the emission of energy and/or mass from the nucleus. When numbers of nuclei are involved, the process is characterized by a definite half-life.

DISINTEGRATION RATE:

1) The absolute rate of decay of a radioactive substance, usually expressed in terms of disintegrations per unit of time.
2) The absolute rate of the transformation of a nuclide under bombardment.

DOSAGE: The process of administering or receiving a dose or, in medical terminology, a planned schedule by which a dose is delivered. Dosage and dose are often used interchangeably, perhaps wrongly so. See Dose.

DOSE: Properly, the absorbed dose from any ionizing radiation. Sometimes the exposure dose, properly expressed in roentgens, which is a measure of the total amount of ionization that the quantity of radiation could produce in air. Sometimes improperly for radiation

outside the applicability of the roentgen, as the ionization which would be produced in air. It is more advisable to restrict the term to the absorbed dose, commonly given in rads. If the biological dose in rems is meant, it should be so stated. See: Absorbed Dose, Rad, RBE, Rem, Rep, Roentgen.

DOSE RATE: Properly, the time rate of absorption of energy from ionizing radiation (rads per hour). Often loosely used for exposure rate, i.e., roentgen per hour, etc. The dose rate is commonly used to indicate the magnitude of prospective exposure.

DOSIMETER: An instrument for measuring and registering total accumulated exposure to ionizing radiations. See Dosimetry.

DOSIMETRY: The theory and application of the principles and techniques involved in the measurement and recording of radiation doses. Its practical aspect is concerned with the use of various type of radiation instruments with which measurements are made. See Chemical Dosimeter, Film Badge, Survey Meter.

DYNE: The unit of force which, when acting upon a mass of one gram, will produce an acceleration of one cm per second per second.

EFFECTIVE HALF-LIFE: Half-Life of a radioactive isotope in a biological organism, resulting from the combination of radioactive decay and biological elimination.

$$\text{Effective half-life} = \frac{\text{Biological half-life} \times \text{Radioactive half-life}}{\text{Biological half-life} + \text{Radioactive half-life}}$$

EFFICIENCY (COUNTERS): A measure of the probability that a count will be recorded when a particle or photon of radiation is incident on a detector. Usage varies considerably so that it is well to make sure which factors (window transmission, sensitive volume, energy dependence, etc.) are included in a given case.

ELECTROMAGNETIC RADIATION: Radiation consisting of alternating electric and magnetic fields at right angles to each other which propagate energy through space in small bundles known as photons or quanta. Gamma and X radiation are examples of electromagnetic radiation.

ELECTRON: A particle of very small mass, carrying a unit negative or positive charge. Negative electrons, surrounding the nucleus, are present in all atoms; their number is equal to the number of positive charges (or protons) in the particular nucleus. The term electron, where used alone, commonly refers to these negative electrons. A positive electron is usually called a positron, and a negative electron is sometimes called a negatron. See Beta Particle.

ELECTRON CAPTURE: A mode of radioactive decay involving the capture of an orbital electron by its nucleus. Capture from a particular electron shell is designated as K-electron capture, L-electron capture, etc.

ELECTRON VOLT (ev): Amount of energy gained by an electron in passing through a potential difference of one volt.

ELEMENT: One of the distinct, basic varieties of matter occuring in nature which, individually or in combination, compose substances of all kinds. Approximately ninety different elements are known to exist in nature and several others, including plutonium, have been obtained as a result of nuclear reactions with these elements.

ENERGY: The capability of doing work. Potential energy is energy due to position of one body with respect to another or to the relative parts of the same body. Kinetic energy is energy due to motion.

ENERGY DEPENDENCE: The characteristic response of a radiation detector to a given range of radiation energies (or wave lengths) as compared with the response of a standard open air chamber.

ENTRY TIME: The time personnel enter a radiation or contamination hazard area.

EPIDERMIS: The outermost layer of cells of the skin.

EPILATION (DEPILATION): The temporary or permanent removal of hair.

EQUILIBRIUM: See Radioactive Equilibrium.

ERG: A unit of work. It is the amount of work done by a force of one dyne acting through a distance of one cm (dyne - cm, or gm - cm^2/sec^2). It is also a unit of energy, being that amount of energy capable of doing one erg of work.

ERYTHEMA: An abnormal redness of the skin, due to distension of the capillaries with blood. It can be caused by many different agents, e. g., heat, certain drugs, ultraviolet rays, ionizing radiation.

EXPOSURE DOSE: See Dose.

EXTERNAL EXPOSURE: Exposure to ionizing radiations coming from a source outside the body.

FALLOUT: The process or phenomenon of the fall back to the earth's surface of particles contaminated with radioactive material from the atomic cloud. The term is also applied in a collective sense to the contaminated particulate matter itself.

FILM BADGE: A small metal or plastic frame, in the form of a badge, worn by personnel, and containing X-ray (or similar photographic) film for estimating the total amount of ionizing radiation to which an individual has been exposed.

FILTER: That material placed over a source of ionizing radiation to alter the quality (spectrum) of the radiation; that material through which liquid or gas is passed which will collect particulate matter.

FIREBALL: See Ball of Fire.

FISSION: The process whereby the nucleus of a particular heavy element splits into (generally) two nuclei of lighter elements, with the release of substantial amounts of energy. The most important fissionable materials are uranium-235 and plutonium-239.

FISSION PRODUCTS: A general term for the complex mixture of substances produced as a result of nuclear fission. A distinction should be made between these and the direct fission products or fission fragments which are formed by the actual splitting of the heavy-element nuclei. Something like 80 different fission fragments result from roughly 40 different modes of fission of a given nuclear species, e.g., uranium-235 or plutonium-239. The fission fragments, being radioactive, immediately begin to decay, forming additional (daughter) products, with the result that the complex mixture of fission products so formed contains about 200 different isotopes of over 30 elements.

FUSION: The process whereby the nuclei of light elements, especially those of the isotopes of hydrogen, namely, deuterium and tritium, combine to form the nucleus of a heavier element with the release of substantial amounts of energy. See Thermonuclear.

GAMMA RAYS (OR RADIATIONS): Electromagnetic radiations of high energy originating in atomic nuclei and accompanying many nuclear reactions, e.g., fission, radioactivity, and neutron capture. Physically, gamma rays are identical with X rays, the only essential difference being that the X rays do not originate from atomic nuclei, but are produced in other ways, e.g., by slowing down (fast) electrons of high energy.

GAS AMPLIFICATION: The ratio of the charge collected in a counter tube or ionization chamber to the charge produced in the active volume by the primary ionizing event.

GEIGER-MUELLER (G-M COUNTER): By popular usage, a Geiger-Mueller counter tube or such tube together with its associated electronic equipment. The G-M tube is a highly sensitive gas-filled radiation measuring device which operates at voltages sufficiently high to produce avalanche ionization.

GEIGER REGION: The voltage interval for a counter tube in which the charge transferred per isolated discharge is independent of the number of primary ions produced in the initial ionizing event.

GEIGER THRESHOLD: The minimum voltage applied to a counter tube for which all pulses produced in the counter tube are of substantially the same size, regardless of the size of the primary ionizing event.

GEOMETRY (RADIATION): Refers to a description of the dimensions and relative spatial position of a radiation source, detector and any object or materials which can absorb, scatter, or alter the radiation being measured. Loosely referred to as the geometry factor, and expressed in percentage.

GROUND ZERO: The point on the surface of land or water vertically below or above the center of a burst or a nuclear (or atomic) weapon; frequently abbreviated to GZ. For a burst over or under water, the term surface zero is preferable.

HALF-LIFE: The time required for the activity of a given radioactive species to decrease to half of its initial value due to radioactive decay. The half-life is a characteristic property of each radioactive species and is independent of its amount or condition. The biological half-life is the time required for the amount of a specified element which has entered the body (or a particular organ) to be decreased to half of its initial value as a result of natural, biological elimination processes. The effective half-life of a given isotope is the time in which the quantity in the body will decrease to half as a result of both radioactive decay and biological elimination.

HALF-VALUE LAYER: The thickness of a given material which will absorb half the gamma radiation incident upon it. This thickness depends on the nature of the material--it is roughly inversely proportional to its density--and also on the energy of the gamma rays.

HEALTH PHYSICS: A term in common use for that branch of radiological physics dealing with the protection of personnel from harmful effects of ionizing radiation. It includes the routine procedures of radiation protection surveys, area and personnel monitoring, the recommendation of appropriate protective equipment and procedures, the determination of acceptable standards of operation, and the solution of problems incident to the effective and practical protection of all persons from harmful effects of radiation.

HOT SPOT: Region in a contaminated area in which the level of radioactive contamination is somewhat greater than in neighboring regions in the area. See Contamination.

INDUCED RADIOACTIVITY: Radioactivity produced in certain materials as a result of nuclear reactions, particularly the capture of neutrons, which are accompanied by the formation of unstable (radioactive) nuclei. The activity induced by neutrons from a nuclear (or atomic) explosion in materials containing the elements sodium, manganese, silicon, or aluminum may be significant.

INTERNAL CONTAMINATION EXPOSURE: The radiation exposure resulting from the deposition of radioactive materials within the body tissues. A continuous, and often long-term, hazard results from the deposit of alpha, beta and/or gamma emitters.

INTERNAL CONVERSION: A mode of radioactive decay in which the excitation energy directly causes the ejection of an orbital electron from the atom.

INITIAL NUCLEAR RADIATION: Nuclear radiation (essentially neutrons and gamma rays) emitted from the ball of fire and the cloud column during the first minute after a nuclear (or atomic) explosion. The time limit of one minute is set, somewhat arbitrarily, as that required for the source of the radiations (fission products in the atomic cloud) to attain such a height that only insignificant amounts reach the earth's surface. See Residual Nuclear Radiation.

INTENSITY: The energy (of any radiation) incident upon (or flowing through) unit area, perpendicular to the radiation beam, in unit time. The intensity of thermal radiation is generally expressed in calories per square centimeter per second falling on a given surface at any specified instant. As applied to nuclear radiation, the term intensity is sometimes used, rather loosely, to express the exposure dose rate at a given location, e.g., in roentgens (or milliroentgens) per hour.

ION: Atomic particle, atom or chemical radical bearing an electrical charge, either negative or positive, due to an excess or deficit of orbital electrons.

IONIZATION: The process or the result of any process by which a neutral atom or molecule acquires either a positive or a negative electrical charge.

IONIZATION CHAMBER: An enclosure containing two or more electrodes between which an electric field is maintained to collect the charge when the enclosed gas is ionized. The ions formed and registered are a measure of the incident radiation which has caused the ionization.

IONIZING RADIATION: Electromagnetic radiation (gamma rays or X-rays) or particulate radiation (alpha particles, beta particles, neutrons, etc.) capable of producing ions, i.e., electrically charged particles, directly or indirectly in its passage through matter.

ION PAIR: A positive ion and a negative ion (usually an electron) having charges of the same magnitude and formed from a neutral atom or molecule, by the action of radiation. A primary ion pair is an ion pair produced by a primary particle or photon.

ISOBAR (nuclear): One of several nuclides having the same number of nucleons in their nuclei and hence having approximately the same atomic mass. For example, phosphorus-32 and sulfur-32 are isobars.

ISODOSE CHART: Chart showing the distribution of radiation in a medium by means of lines or surfaces drawn through points receiving equal doses.

ISOMER: One of several nuclides having the same number of neutrons and protons but capable of existing, for a measurable time, in different quantum states with different energies and radioactive properties. Commonly, the isomer of higher energy decays to one with lower energy by the process of isomeric transition.

ISOMERIC TRANSITION: The process by which a nuclide decays to an isomeric nuclide (i.e., one of the same mass number and atomic number) of lower quantum energy. Isomeric transitions (often abbreviated I.T.) proceed by gamma ray and/or internal conversion electron emission.

ISOTONE: One of several different nuclides having the same number of neutrons in their nuclei, but different numbers of protons.

ISOTOPES: Forms of the same element having identical chemical properties but differing in their atomic masses (due to different numbers of neutrons in their respective nuclei) and in their nuclear properties, e.g., radioactivity, fission, etc. For example, hydrogen

has three isotopes with masses of 1 (hydrogen), 2 (deuterium), and 3 (tritium) units, respectively. The first two of these are stable (nonradioactive) but the third (tritium) is a radioactive isotope. Both of the common isotopes of uranium, with masses of 235 and 238 units respectively, are radioactive, emitting alpha particles, but their half-lives are different. Further, uranium-235 is fissionable by neutrons of all energies, but uranium-238 will undergo fission only with neutrons of high energy.

K - CAPTURE (Electron Capture): Electron capture from the K-shell by the nucleus of the atom.

KELOID: Excessive scar tissue formation following irradiation or other forms of skin injury.

KILOTON ENERGY: The energy of a nuclear (or atomic) explosion which is equivalent to that produced by the explosion of 1 kiloton (1,000 tons) of TNT, i.e., 10^{12} calories or 4.2×10^{19} ergs. See Megaton Energy, TNT Equivalent.

LATENT PERIOD: The period of relative well-being between the initial or prodromal symptoms and the radiation sickness of the acute radiation syndrome. There is also a short period of well-being before the onset of the prodromal symptom that is sometimes called the initial latent period.

LD-50, LD/50, or LD_{50}: Abbreviations for median lethal dose. See Median lethal dose.

LINEAR ABSORPTION COEFFICIENT: See Absorption Coefficient.

MASS ABSORPITON COEFFICIENT: See Absorption Coefficient.

MASS NUMBER: See Nucleus.

MAXIMUM PERMISSIBLE CONCENTRATION (MPC): The highest currently acceptable concentration of radioactive substances (usually expressed as microcuries per cubic centimeter, μc/cc) in air, water, or food to which an individual may be exposed throughout a stated period of time, without expectation of injury.

MAXIMUM PERMISSIBLE DOSE (MPD): That dose of ionizing radiation that a person may receive in his life time without producing any appreciable bodily injury. The presently accepted MPD is (N-18) x 5 rem. N is the individual's age (greater than 18).

MAXIMUM PERMISSIBLE EXPOSURE (MPE): The total amount of radiation exposure to which a normal person may be subjected day-by-day without any harmful effects becoming evident during his lifetime.

MAXIMUM PERMISSIBLE LIMIT (MPL): The total amount of internal contamination and external radiation combined that will not give a dose that will produce appreciable body injury. The term MPL refers to the MPE and MPC collectively and is the sum of the dose from external and internal sources. (MPL = MPE + MPC.) The limits on the dose rates and surface contamination levels necessary to assure compliance with the established total permissible dose are also called MPL's.

MEAN FREE PATH: The average distance a particle travels between collisions.

MEDIAN LETHAL DOSE: The whole-body exposure dose of ionizing radiation expected to be fatal to 50% of a large group of living creatures or organisms. It is commonly (although not universally) accepted, at the present time, that a dose of about 450 roentgens, received over the whole body in the course of a few hours or less, is the median lethal dose for human beings.

MEGATON ENERGY: The energy of a nuclear (or atomic) explosion which is equivalent to 1,000,000 tons (or 1,000 kilotons) of TNT, i.e., 10^{15} calories or 4.2×10^{22} ergs. See TNT Equivalent.

MEV (MILLION ELECTRON VOLTS): A unit of energy commonly used in nuclear physics. It is equivalent to 1.6×10^{-6} ergs. Approximately 200 Mev of energy are produced for every nucleus that undergoes fission.

MICROCURIE (μc): A one-millionth part of a curie.

MICRON: A one-millionth part of a meter.

MILLICURIE (mc): A one-thousandth part of a curie.

MILLIROENTGEN: A one-thousandth part of a roentgen. See Roentgen.

MODERATOR: Material used to slow down particles, usually neutrons, from the high energies at which they are released. Materials high in hydrogen content are most effective in moderating neutrons.

MOLECULE: Unit quantity of a compound (2 or more atoms in chemical combination) which can exist by itself and retain all the chemical and some of the physical properties of the original substance.

MONITORING: The procedure or operation of locating (and measuring) radioactive contamination by means of survey instruments which can detect and measure (as dose rates) ionizing radiations. The individual performing the operation is called a monitor.

MONOCHROMATIC RADIATION: Electromagnetic radiation of a single wave length, or in which all the photons have the same energy.

MONOENERGETIC RADIATION: Particulate radiation of a given type (alpha, beta, neutron, proton, etc.) in which all particles have the same energy.

NEUTRON: A neutral particle, i.e., with no electrical charge, of approximately unit mass, present in all atomic nuclei, except those of ordinary (or light) hydrogen. Neutrons are required to initiate the fission process, and large numbers of neutrons are produced by both fission and fusion reactions in nuclear (or atomic) explosions.

NEUTRON-INDUCED ACTIVITY: Radioactivity produced in a nucleus from neutron capture.

NUCLEAR RADIATION: Particulate and electromagnetic radiation emitted from atomic nuclei in various nuclear processes. The important nuclear radiations are alpha and beta particles, gamma rays, and neutrons. All nuclear radiations are ionizing radiations, but the reverse is not true; X rays, for example, are included among ionizing radiations, but they are not nuclear radiations since they do not originate from atomic nuclei. See Ionizing Radiation.

NUCLEON: Common name for a constituent particle of the nucleus. At present applied to protons and neutrons but will include any other particle found to exist in the nucleus.

NUCLEUS (OR ATOMIC NUCLEUS): The small, central, positively charged region of an atom which carries essentially all the mass. Except for the nucleus of ordinary (light) hydrogen, which is a single proton, all atomic nuclei contain both protons and neutrons. The number of protons determines the total positive charge, or atomic number; this is the same for all the atomic nuclei of a given chemical element. The total number of neutrons and protons, called the mass number, is closely related to the mass (or weight) of the atom. The nuclei of isotopes of a given element contain the same number of protons, but different numbers of neutrons. They thus have the same atomic number, and so are the same element, but they have different mass numbers (and masses). The nuclear properties, e.g., radioactivity, fission, neutron capture, etc., of an isotope of a given element are determined by both the number of neutrons and the number of protons.

NUCLIDE: A general term referring to all nuclear species of the chemical elements - both stable (about 270) and unstable (about 500). A species of atom is characterized by the constitution of its nucleus. The nuclear constitution is specified by the number of protons, Z, number of neutrons, N, and energy content.

PAIR PRODUCTION: An absorption process for X and gamma radiation in which the incident photon is annihilated in the vicinity of the nucleus of the absorbing atom, with subsequent production of an electron and positron pair. This reaction does not occur for incident radiation energies of less than 1.02 Mev.

PERSONNEL DECONTAMINATION: The removal of radioactive materials from human skin by appropriate mechanical and/or chemical means.

PERSONNEL DECONTAMINATION CENTER: The space aboard ship, or in the building or area in which an individual who has been exposed to radioactive contamination may (1) have his clothing and person monitored for radioactivity, (2) remove radioactivity from his person by bathing and/or chemical procedures, (3) have issued to him clean clothing and dosimetry devices before starting work. Also referred to as Change Station or Change House.

PERSONNEL MONITORING: The determination of the degree of radioactive contamination on individuals, using standard survey meters, and the determination of the dose received by means of dosimeters.

PHOTODOSIMETRY: Determination of the cumulative dose of ionizing radiation by use of photographic film.

PHOTOELECTRIC EFFECT: A process by which a photon ejects an electron from an atom. All the photon's energy is absorbed by the atom with resultant ejection of an orbital electron.

PLATEAU (G-M): The level portion of the counting-rate vs voltage curve where changes in operating voltage introduce minimum changes in the counting rate.

PLATEAU SLOPE (Relative); The relative increase in the number of counts as a function of voltage expressed in percentage per 100 volts increase above the Geiger threshold.

POSITRON: A particle from the nucleus or occurring in pair production equal in mass to the electron and having an equal but opposite (positive) charge. Its mass is 0.000548 mass units.

PRODROMAL PHASE: The transient symptoms of sickness which come very soon after large doses of radiation. It is usually followed by a shorter or longer symptom-free interval, usually called the latent period.

PROMPT RADIATION: All ionizing radiation emitted during the fission and fusion processes of a nuclear weapon. See Initial Radiation.

PROPORTIONAL COUNTER: An instrument in which a gas-filled radiation detection tube generates pulses which are proportional in size to the number of ions formed in the gas by the primary ionizing particles.

PROPORTIONAL REGION: The range of operating voltage for a counter tube or ionization chamber in which the gas amplification is greater than one and in which the charge collected is proportional to the charge produced by the initial ionizing event.

PROTON: A particle of mass (approximately) unity carrying a unit positive charge; it is identical physically with the nucleus of the ordinary (light) hydrogen atom. All atomic nuclei contain protons. See Nucleus.

PULSE HEIGHT SELECTOR: A circuit designed to select and pass voltage pulses of a certain minimum amplitude.

QUENCHING: The process of inhibiting continuous or multiple discharges in a counter tube utilizing gas amplification.

RAD: A unit of absorbed dose of radiation; it represents the absorption of 100 ergs of ionizing radiation per gram of the absorbing material or tissue.

RADIAC: A term referring to radiation-measuring instruments (dosimeters, dose rate meters, laboratory counters and scalers, alpha survey meters, etc.). The term comes from RAdioactivity Detection, Indication, And Computation. Radiac may be used as a noun (e.g., beta-gamma radiacs) or as an adjective (e.g., beta-gamma radiac equipment).

RADIATION: See Electromagnetic Radiation, Ionizing Radiation, Nuclear Radiation, and Thermal Radiation.

RADIATION SYNDROME: See Syndrome.

RADIOACTIVE EQUILIBRIUM: The state which prevails when the ratios between the amounts of successive members of a radioactive decay series remain constant.

RADIOACTIVITY: The spontaneous emission of radiation, generally alpha or beta particles, often accompanied by gamma rays, from the nuclei of an (unstable) isotope. As a result of this emission the radioactive isotope is converted (or decays) into the isotope of a different element which may (or may not) also be radioactive. Ultimately, as a result of one or more stages of radioactive decay, a stable (nonradioactive) end product is formed.

RADIOISOTOPE: An unstable nuclide which emits particulate and/or electromagnetic radiation in the process of transforming to a stable state.

RADIOSENSITIVITY: Relative susceptibility of cells, tissues, organs, organisms, or any substances to the injurious action of radiation. Radioresistance and radiosusceptibility are at present employed in a qualitative or comparative sense, rather than quantitatively.

RADIOLOGICAL SAFETY: The methods, plans, and procedures involved in personnel protective measures against radiological hazards.

RADIOLOGICAL SURVEY: See Monitoring.

RBE (RELATIVE BIOLOGICAL EFFECTIVENESS): The ratio of the number of rads of gamma (or X) radiation of a certain energy which will produce a specified biological effect to the number of rads of another radiation required to produce the same effect is the RBE of this latter radiation.

REM: A unit of biological dose of radiation; the name is derived from the initial letters of the term "rad equivalent man (or mammal)." The radiation dose in rems is equal to the dose in rads multiplied by the RBE of the given radiation (for a specified effect). See RAD, RBE.

REMOVABLE CONTAMINATION: Radioactive contamination which is attached to a surface and which may be removed by contact with skin or clothing, or that which may be removed by physical and/or chemical means.

REP: An obsolete unit of absorbed dose of radiation; the name is derived from the initial letters of the term "roentgen equivalent physical." Basically, the rep is intended to express the amount of energy absorbed per gram of soft tissue as a result of exposure to 1 roentgen of gamma (or X) radiation. This is estimated to be about 93 ergs; although the actual value depends on certain experimental

data which are not precisely known. The rep is thus defined, in general, as the dose (of any ionizing radiation) consisting of the absorption of 93 ergs of energy per gram of soft tissue. For soft tissue, the rep and the rad are essentially the same. See Rad, Roentgen.

RESIDUAL NUCLEAR RADIATION: Nuclear radiation, chiefly beta particles and gamma rays, which persists for some time following a nuclear (or atomic) explosion. The radiation is emitted mainly by the fission products and other bomb residues in the fallout, and to some extent by earth and water constituents, and other materials in which radioactivity has been induced by the capture of neutrons. See Fallout, Induced Radioactivity.

RESOLVING TIME: The minimum time interval between two distinct events which will permit both to be counted. It may refer to an electronic circuit, to a mechanical indicating device, or to a counter tube.

ROENTGEN: A unit of exposure dose of gamma (or X) radiation. It is defined precisely as the quantity of gamma (or X) radiation such that the associated corpuscular emission per 0.001293 gram of air produces, in air, ions carrying one electrostatic unit quantity of electricity of either sign. From the accepted value for the energy lost by an electron in producing a positive-negative ion pair in air, it is estimated that 1 roentgen of gamma (or X) radiation would result in the absorption of 87 ergs of energy per gram of air. (See NBS-62*.)

SCALER: An electronic device which registers current pulses received over a given time interval. Binary Scaler: A scaler whose scaling factor is two per stage. Decade Scaler: A scaler whose scaling factor is a power of 10.

SCATTERING: The diversion of radiation, either thermal or nuclear, from its original path as a result of interactions (or collisions) with atoms, molecules, or larger particles in the atmosphere or other medium between the source of the radiations, e.g., a nuclear (or atomic) explosion, and a point at some distance away. As a result of scattering, radiations (especially gamma rays and neutrons) will be received at such a point from many directions instead of only from the direction of the source.

SCINTILLATION DETECTOR: The combination of phosphor, photomultiplier tube and associated electronic circuits for counting light emissions produced in the phosphor by ionizing radiation.

* Report of the International Commission on Radiological Units and Measurements (ICRU), 1956. April 10, 1957.

SECONDARY RADIATION: Radiation originating as the result of absorption of other radiation in matter It may be either electromagnetic or particulate in nature.

SELF ABSORPTION: Absorption of radiation emitted by radioactive atoms by the matter in which the atoms are located; in particular, the absorption of radiation within a sample being assayed.

SENSITIVE VOLUME: That portion of a counter tube or ionization chamber from which ions formed by ionizing radiation are collected and measured.

SHIELDING: Any material or obstruction which absorbs radiation and thus tends to protect personnel or materials from the effects of a nuclear (or atomic) explosion. A moderately thick layer of any opaque material will provide satisfactory shielding from thermal radiation, but a considerable thickness of material of high density may be needed for nuclear radiation shielding.

SKIN DOSE: The dose at the center of an irradiation field on theskin. It is the sum of the air dose and the backscatter dose.

SMEAR SAMPLE: See Wipe Sample.

SPECIFIC ACTIVITY, ISOTOPE: The total radioactivity of a given isotope per gram of the radioactive isotope.

SPECIFIC IONIZATION: Number of ion pairs per unit length of path produced by ionizing radiations.

SPURIOUS COUNT: Count caused by an agency other than the radiation which it is desired to detect.

STABLE ISOTOPE: An isotope of an element which is not radioactive.

STAY TIME: The period during which personnel are allowed to remain in a radiation and/or contaminated area before accumulating their permissible dose.

SUB-SURFACE BURST: See Underground Burst, Underwater Burst.

SUPERCRITICAL: A term used to describe the state of a given fission system when the quantity of fissionable material is greater than the critical mass under the existing conditions. A highly supercritical system is essential for the production of energy at a very rapid rate so that an explosion may occur. See Critical Mass.

SURFACE BURST: The explosion of a nuclear (or atomic) weapon at the surface of the land or water or at a height above the surface less than

the radius of the fireball at maximum luminosity (in the second thermal pulse). An explosion in which the bomb is detonated actually on the surface is called a contact surface burst or a true surface burst. See Air Burst.

SURFACE ZERO: See Ground Zero.

SURGE (OR SURGE PHENOMENA): See Base Surge.

SURVEY (RADIOLOGICAL): See Monitoring.

SURVEY METER: A portable instrument with a detector, such as a Geiger counter or ionization chamber, used to detect nuclear radiation and to measure the dose rate. See Monitoring.

SYNDROME (RADIATION): The complex of symptoms characterizing the disease known as radiation sickness, resulting from excessive exposure of the whole (or a large part) of the body to ionizing radiation. The earliest of these symptoms are nausea, vomiting, and diarrhea which may be followed by loss of hair (epilation), hemorrhage, inflammation of the mouth and throat, and general loss of energy. In severe cases, where the radiation exposure has been relatively large, death may occur within two to four weeks. Those who survive 6 weeks after the receipt of a single dose of radiation may generally be expected to recover.

SYSTEMIC EFFECT: A generalized body effect pertaining to or affecting the body as a whole. For example, while the damage to bone marrow by radiation may be considered a local effect, the resulting decrease in red blood cells being sent to all parts of the body and the consequent anemia is a systemic effect.

TENTH-VALUE LAYER: The thickness of a given material necessary to reduce the dose rate of a X-ray or gamma-ray beam to one-tenth its original value.

THERMAL ENERGY: The energy emitted from the ball of fire as thermal radiation. The total amount of thermal energy received per unit area at a specified distance from a nuclear (or atomic) explosion is generally expressed in terms of calories per square centimeter. See Thermal Radiation.

THERMAL ENERGY YIELD (OR THERMAL YIELD): The part of the total energy yield of the nuclear (or atomic) explosion which is radiated as thermal energy. As a general rule, the thermal energy is one-third of the total energy of the explosion. It may be expressed in calories, ergs, or in terms of the TNT equivalent.

THERMAL RADIATION: Electromagnetic radiation emitted (in two pulses) from the ball of fire as a consequence of its very high temperature; it consists essentially of ultraviolet, visible, and infrared radiations. In the early stages (first pulse), when the temperature of the fireball is extremely high, the ultraviolet radiation predominates; in the second pulse, the temperatures are lower and most of the thermal radiation lies in the visible and infrared regions of the spectrum.

THERMONUCLEAR: An adjective referring to the process (or processes) in which very high temperatures are used to bring about the fusion of light nuclei, such as those of the hydrogen isotopes, deuterium and tritium, with the accompanying liberations of energy. A thermonuclear bomb is a weapon in which part of the explosion energy results from the thermonuclear fusion reactions. The high temperatures required are obtained by means of a fission explosion. See Fusion.

THRESHOLD DETECTOR: An element (or isotope) in which radioactivity is induced only by the capture of neutrons having energies in excess of a certain threshold value characteristic of the element (or isotope). Threshold detectors are used to estimate the neutron spectrum from a nuclear (or atomic) explosion, i.e., the numbers of neutrons in various energy ranges.

TISSUE DOSE: The radiation dose received by a tissue in the region of interest. The rad is the unit of tissue dose.

TNT EQUIVALENT: A measure of the energy released in the detonation of a nuclear (or atomic) weapon, or in the explosion of a given quantity of fissionable material, expressed in terms of the quantity of TNT which would release the same amount of energy when exploded. The TNT equivalent is usually stated in kilotons or megatons. The basis of the TNT equivalence is that the explosion of 1 ton of TNT releases 10^9 calories of energy. See Kiloton, Megaton, Yield.

UNDERGROUND BURST: The explosion of a nuclear (or atomic) weapon with its center beneath the surface of the ground.

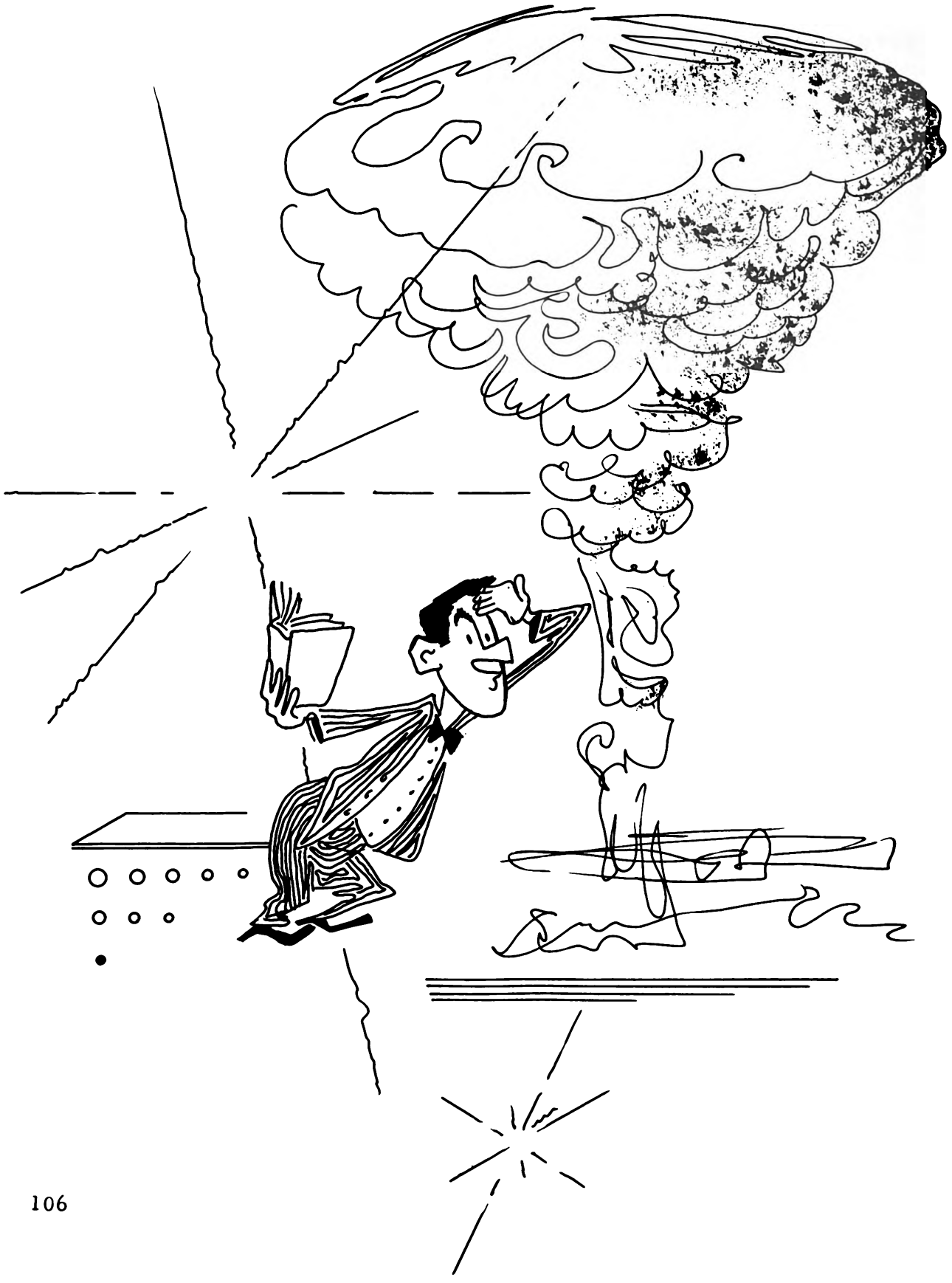
UNDERWATER BURST: The explosion of a nuclear (or atomic) weapon with its center beneath the surface of the water.

WHOLE-BODY EXPOSURE: An exposure of the body to radiation where a major portion of the body, rather than an isolated part, is irradiated. Where a radioisotope is uniformly distributed throughout the body tissues, rather than being concentrated in certain organs, the irradiation can be considered as whole-body exposure.

WIPE SAMPLE: A sample made for the purpose of determining the presence of removable radioactive contamination on a surface. It is done by wiping, with slight pressure, a piece of soft filter paper over a representative area of surface.

X RAYS: Penetrating electromagnetic radiation having wave lengths very much shorter than those of visible light. They are usually produced by bombarding a metallic target with fast electrons in a high vacuum. In nuclear reactions it is customary to refer to photons originating in the nucleus as gamma rays, and to those originating in the extranuclear part of the atom as X rays. These rays are sometimes called roentgen rays, after their discoverer, W. C. Roentgen.

YIELD (OR ENERGY YIELD): The total effective energy released in a nuclear (or atomic) explosion. It is usually expressed in terms of the equivalent tonnage of TNT required to produce the same energy release in an explosion. The total energy yield is manifested as nuclear radiation, thermal radiation, and shock (and blast) energy, the actual distribution being dependent upon the medium in which the explosion occurs (primarily) and also upon the type of weapon and the time after detonation.



APPENDIX A

FORMULAE, GRAPHS, AND TABLES FOR HEALTH PHYSICS COMPUTATIONS

FIGURES

TABLES

APPENDIX A

FORMULAE, GRAPHS, AND TABLES FOR HEALTH PHYSICS COMPUTATIONS

The collection of health physics data presented in this Appendix is a more comprehensive compilation of formulae, tables and graphs than that presented in Volume II. These data are presented so the health physicists or rad-safe officers may readily calculate various dose and dose rate relationships for gamma, beta, and neutron shielding and radiation situations.

A-1 Dose Rate from a Point Source

a. Gamma: The exposure dose rate from a gamma point source may be approximated to within 20% by the formula:

$D_1 = 6\,C\,E$, where

D_1 is the dose rate in r/hr at 1 foot from the source

C is the number of curies

E is the sum of all the gamma emissions of the isotope per disintegration in Mev.

Table A-1 of this Appendix is a tabulation of the dose rate output of the more common radioisotopes.

b. Beta: The dose rate from point beta sources may be estimated ($\pm$ 30%) from Fig. A-1, page 118. An estimate for absorption by the air surrounding the source has been made but is probably underestimated in the dashed regions of the curves.

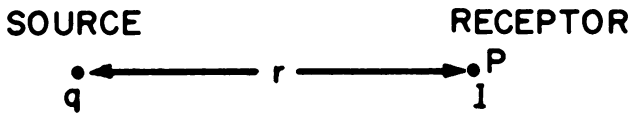
A-2 Gamma Ray Dose Distribution in Air from Various Sources

The gamma ray dose rate from a source is characterized by the gamma ray energy, number of disintegrations per unit time, and the distance from the source. For a fixed disintegration rate of 1 millicurie (assuming one gamma photon per disintegration), the dose rate per hour at 1 cm in air from a point source of a radioisotope is a characteristic constant. Fig. A-2 is a plot of the gamma ray dose rate constant, Γ, for a gamma ray point source in air as a function of energy in Mev. A value of 34 ev to produce one ion pair was used in plotting Γ. It is to be noted that the ordinate of Fig. A-2, Γ, is in units of r/(mc-hr) at one

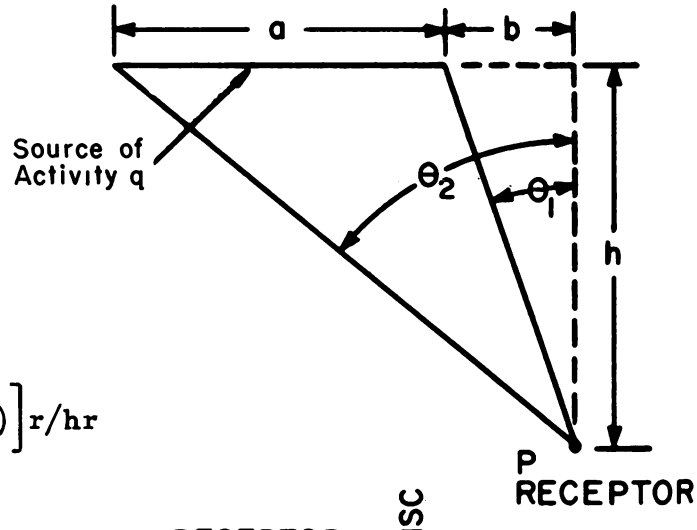
cm in air and assumes 1 gamma photon per disintegration. If there is more than 1 photon per disintegration, Γ must be computed as $\Sigma P_i \Gamma_i$; if less than 1, as $P_i \Gamma_i$. P_i is the fraction of gamma photons of energy E_i emitted per disintegration, and Γ_i is the dose rate constant for energy E_i. (Fig. A.2.) The gamma ray dose rates from various geometries follow where q is the total source activity in millicuries (uniformly distributed), distances are in centimeters, and angles are in radians.

POINT SOURCE

$$I = \frac{q\Gamma}{r^2} \text{ r/hr}$$



LINE SOURCE

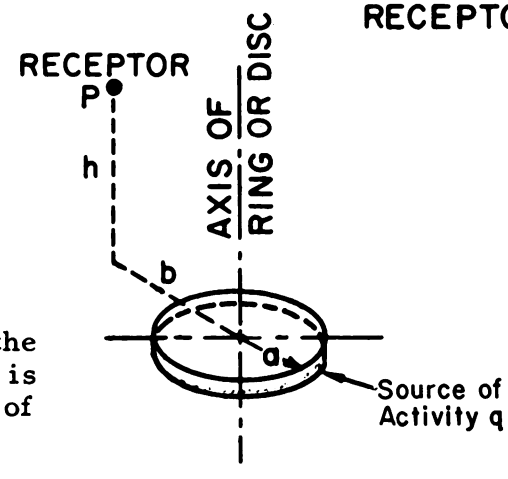


$$I = \frac{q\Gamma}{ah} (\theta_2 - \theta_1) \text{ r/hr} \quad \text{or}$$

$$I = \frac{q\Gamma}{ah} \left[\tan^{-1}\left(\frac{a+b}{h}\right) - \tan^{-1}\left(\frac{b}{h}\right)\right] \text{r/hr}$$

RING SOURCE

$$I = \frac{q\Gamma}{\left[(a^2+b^2+h^2)^2 - 4a^2 b^2\right]^{1/2}} \text{ r/hr}$$



where b is the perpendicular from P to the axis of the ring of radius a, and where h is the vertical distance from P to the plane of the ring.

DISC SOURCE where b is the perpendicular from P to the axis of the disc of radius a, and where h is the vertical distance from P to the plane of the disc.

$$I = \frac{q\Gamma}{a^2} \ln \left[\frac{a^2-b^2+h^2+\sqrt{(a^2-b^2+h^2)^2+4b^2h^2}}{2h^2} \right] r/hr.$$

For points on the central axis where b=0,

$$I = \frac{q\Gamma}{a^2} \ln \frac{(h^2+a^2)}{h^2} r/hr.$$

A-3 Gamma Ray Absorption in Source and Capsule

Although sources may be considered mathematically as lines, circles or disks, in practice, sources must have a finite thickness. Therefore some of the gamma rays are absorbed in the source itself. The exact calculation of the gamma-ray absorption is difficult to perform, but useful approximations may be made which are valid for the high-atomic-number materials and small thickness usually found in the source and capsule. The dose rate equation should be multiplied by the factor $e^{-\mu x}$ to correct for self-absorption in the source. μ is the linear absorption coefficient of the source material or capsule and x is its thickness.

A-4 Dose Rate in an Infinite Absorbing Source Material

For a source uniformly distributed throughout an infinite absorbing medium, considerations of the conservation of energy lead to the relationship:

D = 2.30 C E, where

C is the specific activity of the source in μc/gram,

D is dose rate in rads/hour,

E is the mean energy per disintegration in Mev.

This expression also gives the dose rate to a small cavity of inactive material. The dimensions of the cavity must be small compared with the range of the radiation. If the cavity is of different material from the source, a correction factor may be necessary for the different mass absorption coefficients of the materials.

If the active material is confined to the space on one side of a plane, the dose rate at the plane, by symmetry, is

$$D = 1.15\ C\ E\ .$$

This expression may also be applied to the interface of an active material and air although in this case, the absence of backscatter from the inactive half-space causes the dose rate to be over-estimated (varies with conditions and rarely exceeds a factor of 1.5).

Throughout this Appendix, the term "infinite" is used to indicate that the dimensions of a source are such that radiation from a remote region fails to reach the point at which the dose rate is to be assessed. In practice, if the hardest radiation involved has a linear absorption coefficient of μ, the source material should extend for a distance r such that μr exceeds 3 or 4.

A-5 Dose Rate at a Distance from a Thick Source

The dose rate at a distance from a thick source can be estimated from the surface dose rate and the solid angle subtended by the source at the point at which the dose rate is required. The required dose rate is given by

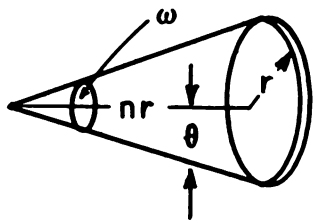
$$D = \frac{\omega D_s}{2\pi}$$

where D_s is the surface dose rate and ω is the solid angle subtended.

This expression assumes that the source is a segment of a spherical shell with the center at the point at which the dose rate is required. The expression for the solid angle subtended by a circular aperture of radius r at a distance nr along the perpendicular to the plane of the aperture through the center of the aperture is frequently applicable.

In this case

$$\omega = 2\pi(1-\cos\theta)$$



where $\theta = \tan^{-1}(\frac{1}{n})$ and is the semiangle of the subtending cone.

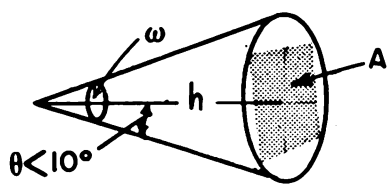
Fig. A-3 is a plot of the solid angles from a disk.

For values of n>6, the solid angle may be approximated to within 3% by:

$$\omega = \pi / n^2$$

The solid angle subtended by a plane square area, A, at a point can be estimated to within 5% if (a) the entire area lies inside a circular cone centered on the perpendicular from the point onto the plane of the area and (b) semiangle is less than 10^{o} by:

$$\omega = A/h^2$$



where A is the plane area and h is the perpendicular distance to the plane.

A-6 Dose Rate from an Infinite and Circular Plane Area

The beta and gamma dose rates from an infinite plane area of active material for various heights above the plane in

air are presented in Figs. A-4 and A-5. Fig. A-6 is a plot of the relative gamma radiation intensities versus height from various circular fields.

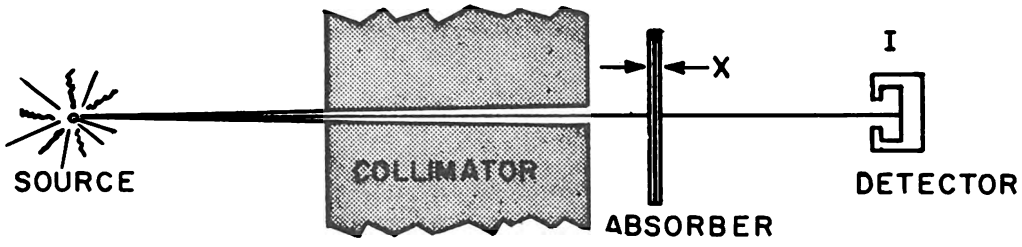
A-7 Gamma Radiation Attenuation

The three main processes by which gamma rays interact with matter are the Compton process, the photoelectric effect, and pair production. Table A-2 lists the total mass absorption coefficients for X and gamma radiation showing the combined effects of all the photon-absorption processes. The mass absorption coefficient, μ_m (cm^2/gm), is related to the linear absorption coefficient, μ (cm^{-1}), by

$$\mu_m = \mu/\rho$$

where ρ is the density of the material in units of gm/cm^3.

a. "Narrow-Beam" Attenuation



Good geometry or narrow-beam photon attenuation is given by

$$I = I_o e^{-\mu x}$$ where

I_o is the dose rate at the detector without the absorber, I is the dose rate at the detector with the absorber, μ is the linear absorption coefficient of the absorber and, x is the thickness of the absorber.

b. Build-Up in Shielding

The mass absorption coefficient gives an accurate estimate of the absorption of radiation only in cases of good geometry. In practical cases of shielding, the scattered radiation contributes to the total emergent radiation an amount of radiation equal in dose rate to (B(x) - 1) times the emergent radiation in good geometry. This factor B(x) is called the dose rate build-up factor and the attenuation in the shield is then given by

$$I = I_o B(x) e^{-\mu x}$$

Figs. A-7 and A-8 present the dose rate build-up factors for water and lead for point and monodirectional sources.

B(x) is plotted against the number of relaxation lengths or mean free paths (μx). One relaxation length, λ, is equal to $1/\mu$. It is the thickness of material necessary to attenuate narrow-beam radiation by a factor e, the base of the natural logarithms. To find the number of relaxation lengths in a material of thickness x, divide the thickness by the relaxation length λ. Thus, the number of relaxation lengths = $x/\lambda = x/(1/\mu) = \mu x$.

c. Transmission of Gamma Rays from a Source

In the foregoing discussion, the distance factor has not been considered. When the distance factor or geometry is taken into account, the attenuation equation becomes

$$I = \frac{I_o \, B(x) \, e^{-\mu x}}{r^2}$$

where r is the distance from the source. A consistent system of units must be used, I_o being expressed as the dose rate at unit distance, I being the dose rate at the distance r, and x the thickness of the absorber.

A-8 Neutron Attenuation

Attenuation of neutrons is a different and more difficult problem than photon attenuation. As far as the latter is concerned, it is merely a matter of interposing a sufficient mass of material between the photon source and the recipient. A different phenomenon is involved in neutron attenuation. Consider the processes of shielding fission neutrons. First the very fast neutrons must be slowed down into the moderately fast range; this requires a suitable inelastic scattering material, such as one containing barium or iron. Then, the moderately fast neutrons have to be decelerated into the slow range by means of an element of low atomic weight such as the hydrogen and oxygen nuclei in water. The slow or thermal neutrons must then be absorbed. Unfortunately, most neutron-capture reactions are accompanied by the emission of photons. Consequently, sufficient gamma shielding must be included to minimize the escape of capture photons from the shielding.

An increase in the absorption of the nuclear radiations can be achieved by using a modified ("heavy") concrete made by adding a considerable proportion of an iron ore, e.g., limonite, to the mix and incorporating small pieces of iron, such as steel punchings. Heavy elements are effective in slowing down very fast neutrons through inelastic scattering and are necessary to attenuate the capture gammas. The presence of boron or a boron compound in neutron shields has the advantage that the B^{10} isotope has a high thermal capture cross section with the emission of 0.48 Mev photon. This 0.48 Mev photon is relatively easy to shield as compared to the 2.23 Mev photon of the hydrogen neutron capture.

The attenuation of a narrow beam of neutrons by a shield can be represented by an equation similar to that used for photons, namely:

$N = N_o \ e^{-\Sigma x}$ where

N_o is the dose rate without the shield,

N is the dose rate penetrating the shield,

x is the shield thickness, and

Σ is the macroscopic cross section

The macroscopic cross section, Σ, is equivalent to the linear absorption coefficient for photon attenuation. Actually, there is a specific value of Σ for every neutron energy and for each type of reaction the neutron can undergo. However, for shielding calculations an empirical Σ, based on actual measurements, is used. It is a weighted average for all the possible neutron interactions over the range of energies involved.

Fig. A-9 presents the half-value thickness for fast-neutron attenuation for ordinary concrete. Fig. A-10 is the Po-Be and Po-B neutron-attenuation data for paraffin and water and should be sufficient data for estimating shields for isotopic sources. Additional neutron-shielding information may be found in physics and reactor texts such as The Reactor Handbook, Volume I, Physics, AECD-3645.

A-9 Beta Particle Attenuation

Figs. A-11 and A-12 are the transmission curves for beta particles in aluminum and are applicable to absorbers with atomic weights ranging between 30 and 60. Error up to 7% is introduced when the atomic weight of the absorber is out of this range. Figure 2.5 (page 27) is a plot of the maximum range of beta particles in various materials.

A-10 Dose and Dose Rate from $t^{-1.2}$ Fission Product Decay

Table A-3 presents correction factors to normalize radiation dose rates to H+1 dose rates. For example, a radiation dose rate of 3 r/hr measured at H+5 hours implies an H+1 dose rate of 3 r/hr x (6.76) or 20 r/hr.

Table A-4 is a fission product accumulated dose table for calculating doses received for various stay and entry times. Table A-4 is based on the H+1 dose rate which may be calculated from Table A-3. Sample problems are given in Table A-4.

A-11 Activity-Mass Relationships

A useful formula for computing the activity of a given mass of a radioisotope is:

$$M = \frac{130,800\ G}{A\ T_{1/2}}$$ where

$T_{1/2}$ is the half-life in days,

M is the activity in millicuries,

A is the atomic mass of the radioactive isotopes,

G is the weight in micrograms.

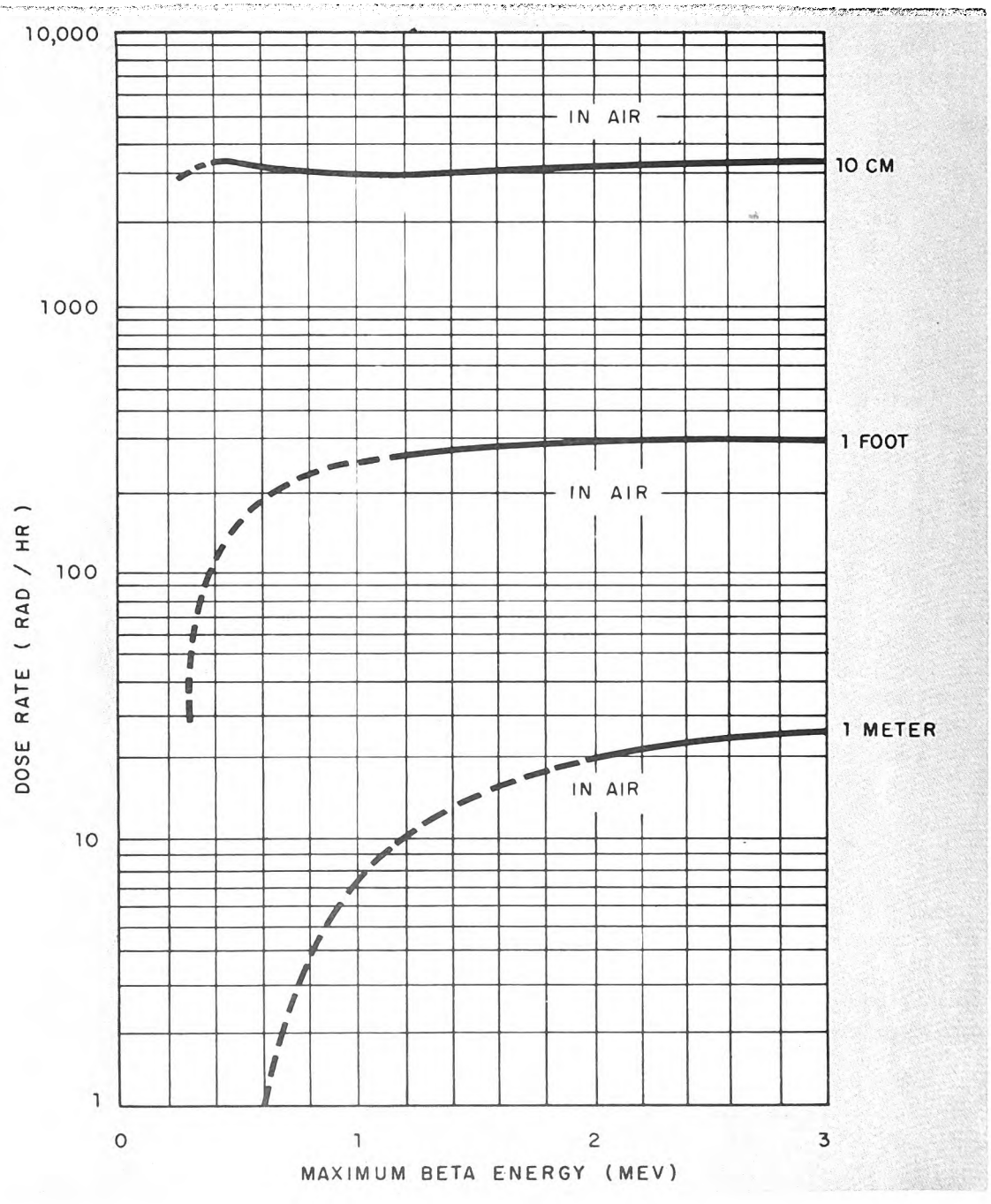
For example, 1 μg of Ca^{45} ($T_{1/2}$ = 152 days) has an activity of:

$$M = \frac{130,800}{45 \times 152} = 19 \text{ millicuries.}$$

Table A-5 lists the activity-mass relationships of the more common radioisotopes.

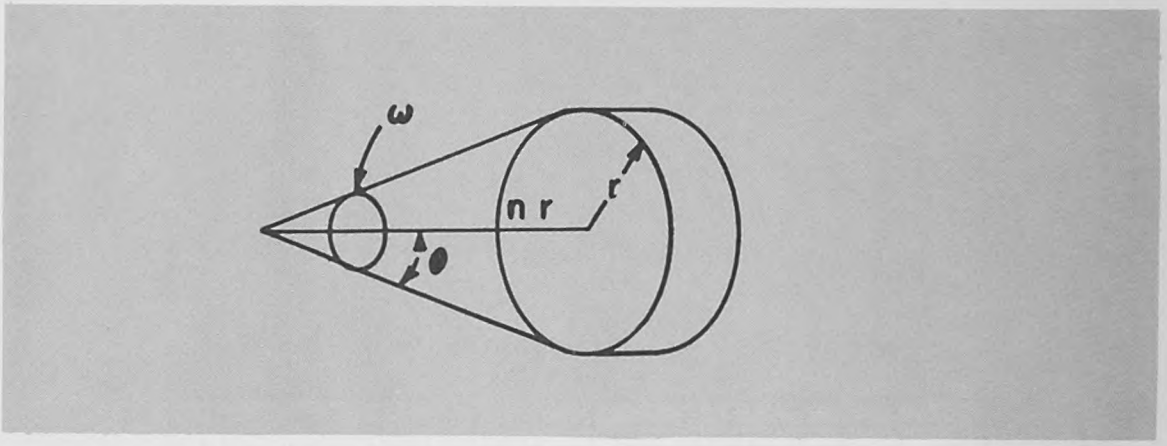
A-12 Applied Physiology

Table A-6 lists the water balance, respiration and retention of particulate matter in the respiratory tract of a standard man for normal activity in a temperate zone.



(Note: Beta energy is maximum of spectrum; mean energy is assumed to be one-third of maximum.)

FIG. A-1 DOSE RATE FROM POINT BETA SOURCE OF STRENGTH 1 BETA CURIE



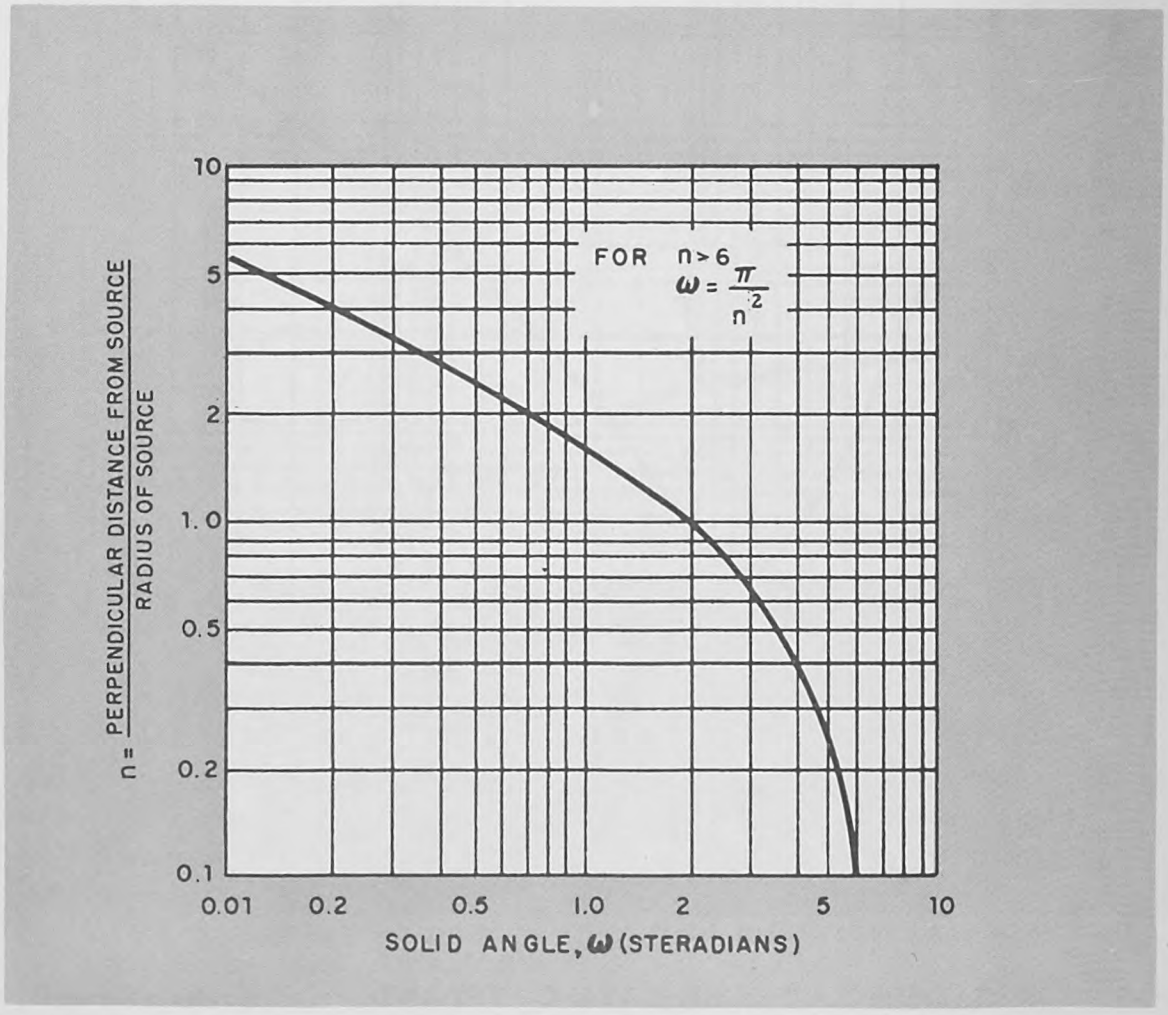


FIG. A-3 SOLID ANGLE SUBTENDING A CIRCULAR AREA

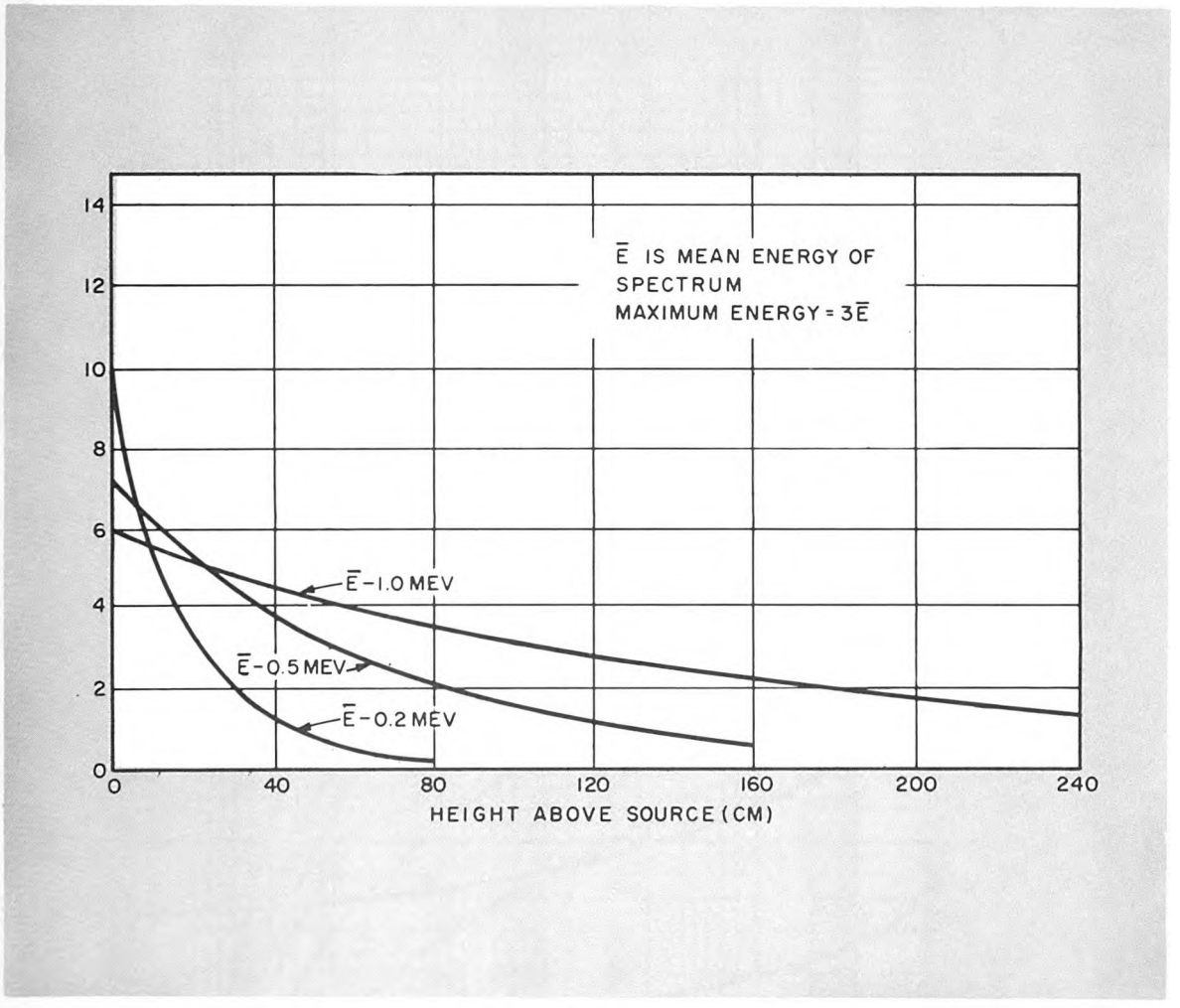


FIG. A-4 DOSE RATE IN AIR FROM BETA EMITTER ON INFINITE PLANE AREA

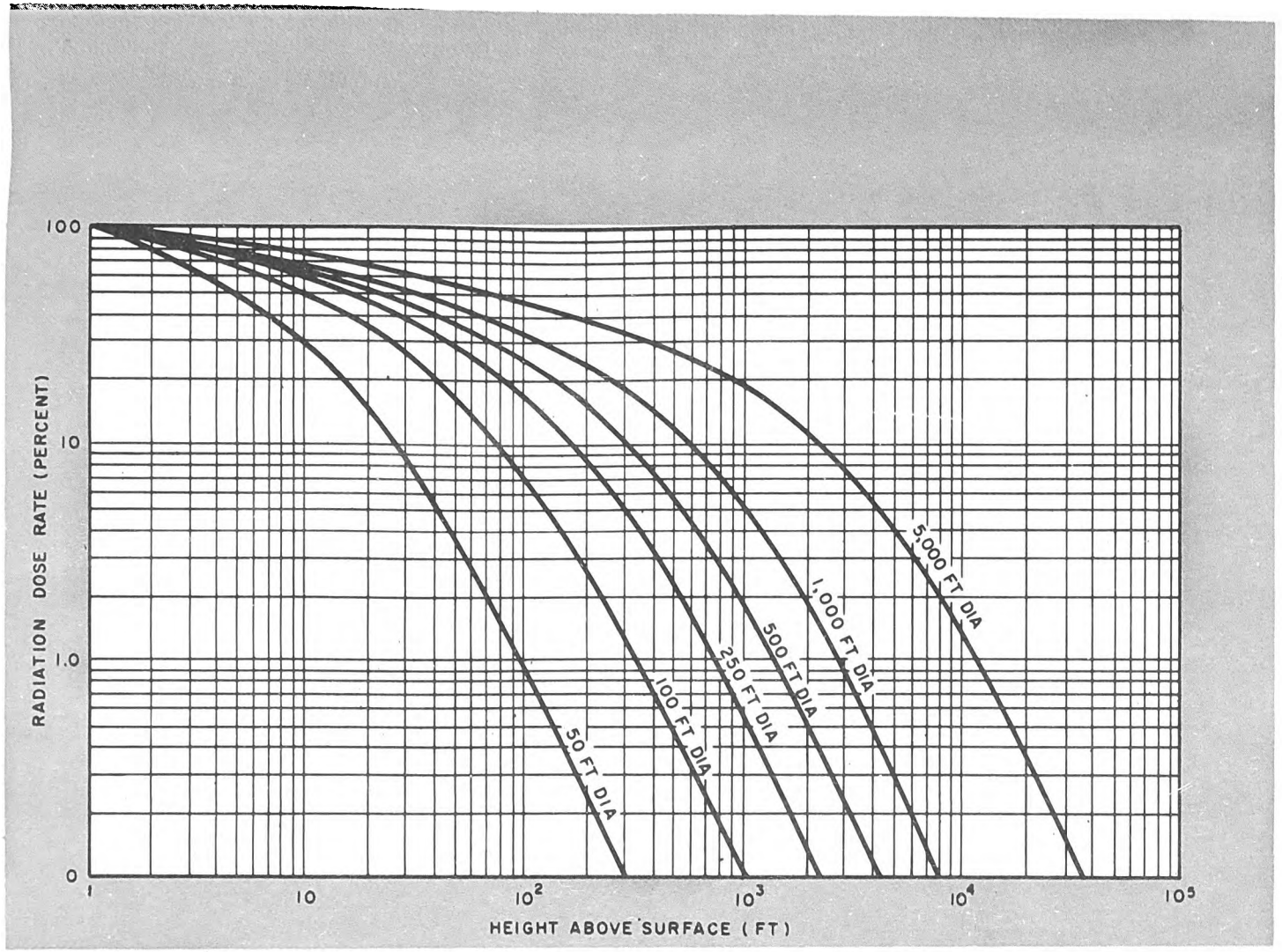


FIG. A-6 THEORETICAL RELATIVE RADIATION DOSE RATE VS HEIGHT FROM VARIOUS CIRCULAR FIELDS (NORMALIZED TO 100% DOSE RATE AT 1 FT)

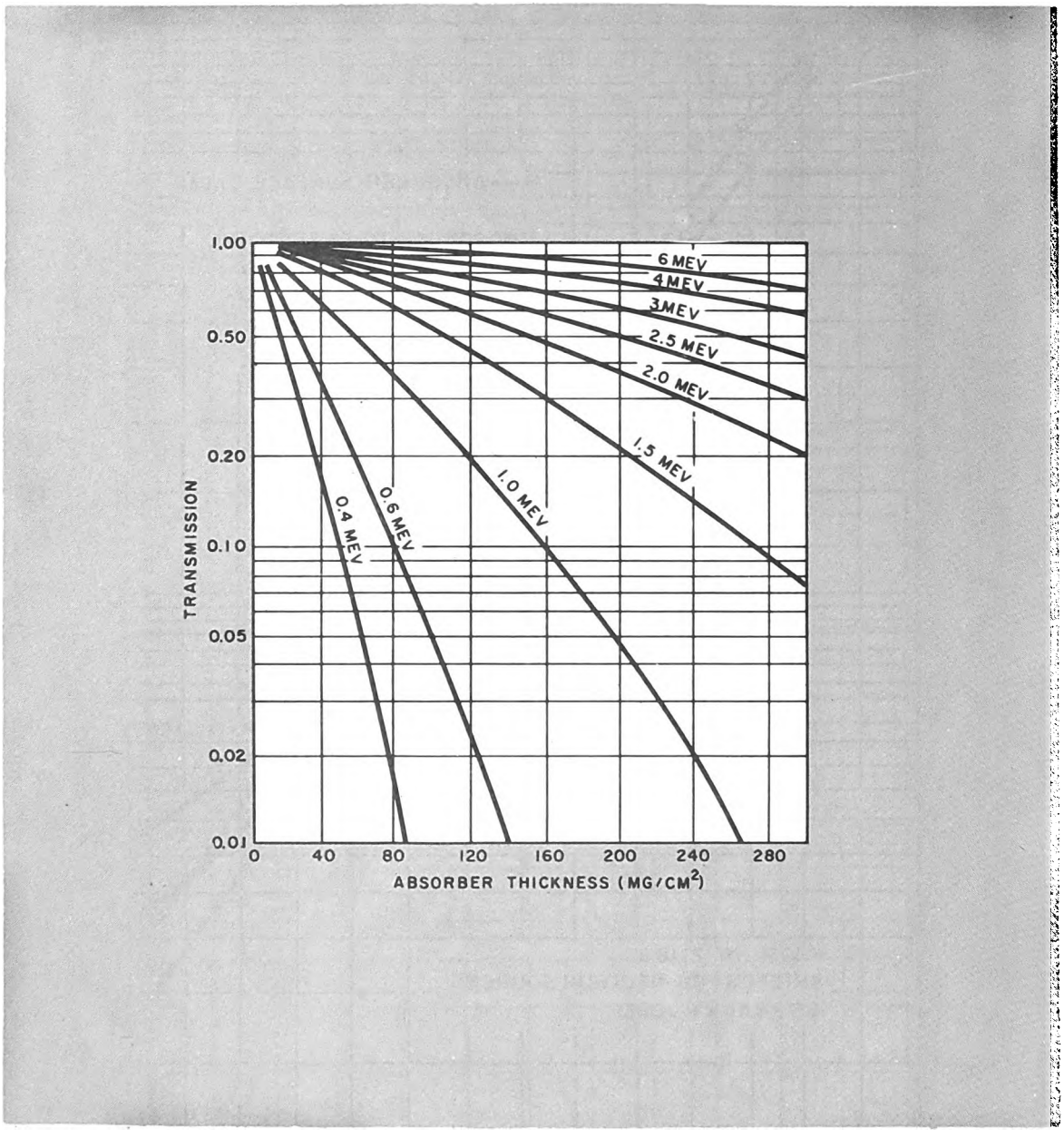


FIG. A-11 TRANSMISSION OF BETA SPECTRA THROUGH ALUMINUM

TABLE A-I

CALCULATED GAMMA RADIATION LEVELS FOR ONE CURIE OF SOME RADIOISOTOPES[1]

Isotope	Annihilation Radiation	QUANTUM ENERGY (E) IN MEV Nuclear gamma radiation (number in parentheses indicates photons/dis)	Dose Rate at 1 Yard (r/hr)	Dose Rate at 1 Meter (r/hr)
Na^{22}	0.51 (2)	1.28 (1)	1.51	1.26
Na^{24}		1.38 (1) 2.76 (1)	2.31	1.93
Mn^{52}	0.51 (0.7)	0.73 (1) 0.94 (1) 1.46 (1)	2.30	1.92
Mn^{54}		0.84 (1)	0.54	0.45*
Fe^{59}		0.2 (0.03) 1.1 (0.57) 1.3 (0.43)	0.77	0.65
Co^{58}	0.51 (0.3)	0.81 (1)	0.67	0.56*
Co^{60}		1.17 (1) 1.33 (1)	1.59	1.32
Cu^{64}	0.51 (0.38)		0.137	0.114
Zn^{65}	0.51 (0.04)	1.12 (0.47)	0.36	0.30*
I^{130}		0.417 (0.4) 0.537 (1) 0.667 (1) 0.744 (1)	1.48	1.23
I^{131}		0.080 (0.063) 0.284 (0.063) 0.364 (0.809) 0.637 (0.093) 0.722 (0.028)	0.276	0.231
Cs^{137}		0.661 (0.92)	0.426	0.356
Ir^{192}		20 known lines 0.136 to 1.157 Mev	0.61	0.51
Au^{198}		0.411 (1) 0.68 (0.013) 1.09 (0.0025)	0.297	0.248
Ra^{226} & equilibrium decay products		Many known lines	1.005**	0.84**

* Isotopes have X-ray emission following electron capture whose contribution to I is negligible at 1 meter but would not be at distances of the order of 1 cm. Self absorption is ignored.

** With 0.5 mm Pt filter. This figure is the average of better measurements.

1 Excerpt from Radiological Health Handbook PB 121784, U. S. Dept. of Public Health, Education and Welfare, January 1957.

TABLE A-2

TOTAL MASS ABSORPTION COEFFICIENTS FOR X AND GAMMA RADIATIONS[1]

Photon Energy Mev	Carbon	Air	Water	Aluminum	Iron	Copper	Lead	Uranium	Concrete $\rho = 2.35$
			mass absorption coefficients in cm^2/gram						
0.01	2.28	5.09	5.31	26.8	179	225	84.6	118	24.6
.01307							41.9		
.015	.777	1.59	1.64	8.08	58.8	76.8		40.2	7.68
.01589							135		
.01720								28.3	
.02	.429	.764	.789	3.48	26.3	34.6	72.0		3.34
.02181								76.6	
.03	.252	.349	.370	1.13	8.26	11.1	23.5	31.9	1.10
.04	.205	.245	.264	.558	3.64	4.83	10.5	14.3	.542
.05	.185	.204	.222	.360	1.93	2.56	5.73	7.79	.350
.06	.174	.186	.204	.270	1.20	1.58	3.55	4.73	.267
.08	.161	.166	.183	.198	.595	.762	1.66	2.22	.197
.08823							1.30		
							7.63		
.10	.152	.155	.171	.169	.372	.461	5.47	1.26	.169
.1163								.865	
								4.79	
.15	.135	.136	.151	.138	.196	.222	1.92	2.52	.139
.20	.123	.123	.137	.122	.146	.156	.942	1.22	.124
.30	.107	.107	.119	.104	.110	.112	.377	.476	.107
.40	.0953	.0954	.106	.0927	.0940	.0940	.220	.273	.0954
.50	.0870	.0868	.0966	.0844	.0840	.0834	.152	.185	.0870
.60	.0805	.0804	.0896	.0779	.0769	.0760	.119	.142	.0804
.80	.0707	.0706	.0786	.0683	.0669	.0659	.0866	.0987	.0706
1.0	.0636	.0635	.0706	.0614	.0599	.0589	.0704	.0779	.0635
1.5	.0518	.0517	.0575	.0500	.0485	.0476	.0522	.0559	.0517
2.0	.0444	.0445	.0493	.0432	.0424	.0418	.0463	.0490	.0445
3.0	.0356	.0357	.0396	.0353	.0360	.0357	.0423	.0448	.0363
4.0	.0304	.0307	.0339	.0310	.0330	.0330	.0421	.0441	.0317
5.0	.0270	.0274	.0301	.0282	.0313	.0316	.0426	.0446	.0287
6.0	.0245	.0250	.0275	.0264	.0304	.0309	.0436	.0455	.0268
8.0	.0213	.0220	.0240	.0241	.0295	.0303	.0459	.0479	.0243
10	.0194	.0202	.0219	.0229	.0294	.0305	.0489	.0511	.0229
15	.0166	.0178	.0190	.0215	.0304	.0318	.0554	.0586	.0214
20	.0154	.0166	.0177	.0212	.0315	.0334	.0611	.0646	.0209
30	.0142	.0158	.0166	.0214	.0339	.0362	.0697	.0738	.0209
40	.0139	.0156	.0162	.0220	.0359	.0385	.0759	.0804	.0213
50	.0138	.0157	.0161	.0225	.0376	.0404	.0805	.0855	.0217
60	.0138	.0158	.0161	.0231	.0391	.0420	.0843	.0895	.0222
80	.0139	.0160	.0163	.0240	.0412	.0442	.0899	.0956	.0230
100	.0141	.0164	.0166	.0247	.0427	.0460	.0939	.0998	.0237

[1]Abstracted from NBS CIRCULAR 583, X-ray Attenuation Coefficients from 10 Kev to 100 Mev.

TABLE A-3

CORRECTION OF R/HR AT ANY TIME TO 1 HOUR AFTER BURST

Time After Burst	Factor	Time After Burst	Factor	Time After Burst	Factor
0:00	------	2:00	2.28	11:00	17.2
0:05	0.050	2:05	2.40	11:30	18.2
0:10	.121	2:10	2.52	12:00	19.1
0:12	.149	2:15	2.63	12:30	20.0
0:14	.181	2:20	2.75	13:00	21.0
0:16	.211	2:25	2.86	13:30	21.9
0:18	.244	2:30	2.98	14:00	22.9
0:20	.278	2:35	3.10	14:30	23.9
0:22	.306	2:40	3.23	15:00	25.0
0:24	.323	2:45	3.35	15:30	26.0
0:26	.377	2:50	3.48	16:00	27.0
0:28	.410	2:55	3.60	16:30	27.9
0:30	.444	3:00	3.70	17:00	28.8
0:32	.481	3:05	3.82	17:30	30.0
0:34	.512	3:10	3.95	18:00	31.0
0:36	.550	3:15	4.08	18:30	32.0
0:38	.589	3:20	4.20	19:00	33.2
0:40	.621	3:25	4.31	19:30	34.1
0:42	.658	3:30	4.45	20:00	35.2
0:44	.695	3:40	4.70	21:00	37.2
0:46	.730	3:50	4.93	22:00	39.6
0:48	.770	4:00	5.19	23:00	41.7
0:50	.813	4:10	5.43	24.00	43.9
0:52	.848	4:20	5.72	25:00	46.1
0:54	.886	4:30	5.95	26:00	48.4
0:56	.926	4:40	6.17	27:00	50.5
0:58	.962	4:50	6.49	28:00	52.8
1:00	1.000	5:00	6.76	29:00	54.9
1:02	1.042	5:15	7.15	30:00	57.5
1:04	1.070	5:30	7.52	32:00	62.1
1:06	1.117	5:45	7.95	34:00	66.7
1:08	1.162	6:00	8.33	36:00	71.5
1:10	1.198	6:15	8.78	38:00	75.7
1:12	1.242	6:30	9.18	40:00	80.6
1:14	1.290	6:45	9.62	42:00	85.0
1:16	1.325	7:00	10.00	44:00	90.0
1:18	1.360	7:15	10.42	46:00	94.3
1:20	1.409	7:30	10.88	48:00	100.0
1:22	1.450	7:45	11.3	50:00	106.3
1:24	1.493	8:00	11.8	55:00	117
1:26	1.537	8:30	12.7	60:00	130
1:28	1.588	8:45	13.1	65:00	142
1:30	1.621	9:00	13.5	70:00	155
1:35	1.740	9:15	14.0	72:00	160
1:40	1.852	9:30	14.5	100:00	238
1:45	1.961	9:45	15.0	500:00	1850
1:50	2.06	10:00	15.4		
1:55	2.18	10:30	16.0		

INSTRUCTIONS AND SAMPLE CALCULATION FOR TABLE A-3

(1) From observed radiation dose rate at a given time compute the radiation dose rate at 1 hour after the burst.

Solution: Look up the factor corresponding to the time of the original reading. Multiply this reading by the factor.

SAMPLE: At 1 hour and 55 minutes after the burst a reading of 31 r/hr was observed. The factor corresponding to 1 hour and 55 minutes (1:55) is 2.18. The observed reading is multiplied by this factor, i.e., 31 x 2.18 = 67.6 r/hr at 1 hour.

(2) From known dose rate at 1 hour after the burst compute it at any other time (less frequently done).

Solution: Look up the factor corresponding to the time desired and divide it into the rate at 1 hour.

TABLE A-4

FISSION PRODUCT ACCUMULATED DOSE TABLE

Time After Burst	Roentgens per hour at 1 hour after burst															
	1	5	10	15	20	25	30	40	50	60	70	80	90	100	150	200
0:00	----	----	----	----	----	----	----	---	---	---	---	----	----	----	----	----
0:02	1.40	7.0	14.0	21.0	28.0	35	42	56	70	84	98	112	126	140	210	280
0:03	2.25	12.5	22.0	34.5	44.0	57	66	88	125	132	154	176	213	220	345	440
0:04	2.80	14.0	28.0	42.0	56.0	70	84	112	140	168	196	224	252	280	420	560
0:05	3.15	15.8	31.5	47.3	63.0	89	104	146	158	208	250	292	304	315	470	630
0:08	3.90	19.5	39.0	58.5	78.0	98	117	156	195	234	273	312	351	390	585	780
0:10	4.20	21.0	42.0	63.0	84.0	105	126	168	210	252	294	336	378	420	630	840
0:12	4.45	22.3	44.5	66.8	89.0	111	134	178	223	268	312	356	401	445	668	890
0:14	4.67	23.4	46.7	70.1	93.4	117	140	187	234	280	327	374	421	467	701	934
0:16	4.85	24.3	48.5	72.8	97.0	121	146	197	243	292	340	388	437	485	728	970
0:18	5.00	25.0	50.0	75.0	100.0	125	150	200	250	300	350	400	450	500	750	1,000
0:20	5.15	25.8	51.5	77.3	103.0	129	155	206	258	310	361	412	464	515	773	1,030
0:22	5.23	26.2	52.3	78.5	105.0	131	157	210	262	314	367	420	472	523	785	1,050
0:24	5.35	26.8	53.5	80.3	107.0	134	160	214	268	320	374	428	482	535	803	1,070
0:26	5.43	27.2	54.3	81.5	109.0	136	163	218	272	326	381	436	490	543	815	1,090
0:28	5.53	27.7	55.3	83.0	111.0	139	166	222	277	332	388	444	499	553	830	1,110
0:30	5.60	28.0	56.0	84.0	112.0	140	168	224	280	336	392	448	504	560	840	1,120
0:35	5.75	28.8	57.5	86.3	115.0	144	173	230	288	346	403	460	518	575	863	1,150
0:40	5.90	29.5	59.0	88.5	118.0	148	177	236	295	354	413	472	531	590	885	1,180
0:45	6.03	30.2	60.3	90.5	121.0	151	181	242	305	362	423	484	544	603	905	1,210
0:50	6.13	30.7	61.3	92.0	123.0	154	184	246	307	368	430	492	553	613	920	1,230
0:55	6.23	31.2	62.3	93.5	125.0	156	187	250	312	374	437	500	562	623	935	1,250
1:00	6.30	31.5	63.0	94.5	126.0	158	189	252	315	378	441	504	567	630	945	1,260
1:05	6.40	32.0	64.0	96.0	128.0	160	192	256	320	384	448	512	576	640	960	1,280
1:10	6.50	32.5	65.0	97.5	130.0	163	195	260	325	390	455	520	585	650	975	1,300
1:20	6.63	33.2	66.3	99.5	133.0	166	199	266	332	398	465	532	598	663	995	1,330
1:30	6.73	33.7	67.3	101.0	135.0	169	202	270	337	404	472	540	607	673	1,010	1,350
1:40	6.83	34.2	68.3	103.0	137.0	171	205	274	342	410	479	548	616	683	1,030	1,370
1:50	6.92	34.6	69.2	104.0	138.0	173	207	276	346	414	483	552	622	692	1,040	1,380
2:00	7.00	35.0	70.0	105.0	140.0	175	210	280	350	420	490	560	630	700	1,050	1,400
2:15	7.10	35.5	71.0	106.0	142.0	178	212	284	355	424	496	568	639	710	1,060	1,420
2:30	7.20	36.0	72.0	108.0	144.0	180	216	288	360	432	504	576	648	720	1,080	1,440
2:45	7.26	36.3	72.6	109.0	145.0	181	218	290	363	436	508	580	653	726	1,090	1,450

TABLE A-4 (Cont'd)

Time After Burst	Roentgens per hour at 1 hour after burst.															
	1	5	10	15	20	25	30	40	50	60	70	80	90	100	150	200
3:00	7.33	36.7	73.3	110.0	147.0	184	220	294	367	440	514	588	661	733	1,110	1,470
3:30	7.43	37.2	74.3	112.0	149.0	186	223	298	372	446	521	596	670	743	1,120	1,490
4:00	7.55	37.8	75.5	113.0	151.0	189	226	302	378	452	528	604	680	755	1,130	1,510
4:30	7.65	38.3	76.5	115.0	153.0	191	230	306	383	460	536	612	689	765	1,150	1,530
5:00	7.75	38.8	77.5	116.0	155.0	194	232	310	388	464	542	620	698	775	1,160	1,550
6:00	7.87	39.9	78.7	119.0	157.0	197	238	314	399	476	552	628	713	787	1,190	1,570
7:00	7.97	40.0	79.7	120.0	160.0	200	240	320	400	480	560	640	720	797	1,200	1,600
8:00	8.06	40.3	80.6	121.0	161.0	201	242	322	403	484	564	644	725	806	1,210	1,610
9:00	8.15	40.8	81.5	122.0	163.0	204	244	326	408	488	570	652	734	815	1,220	1,630
10:00	8.20	41.0	82.0	123.0	164.0	205	246	328	410	492	574	656	738	820	1,230	1,640
13:00	8.40	42.0	84.0	126.0	168.0	210	252	336	420	504	588	672	756	840	1,260	1,680
17:00	8.52	42.6	85.2	128.0	170.0	213	256	340	426	512	596	680	766	852	1,280	1,700
20:00	8.62	43.1	86.2	129.0	172.0	215	258	344	431	516	602	688	775	862	1,290	1,720
24:00	8.72	43.6	87.2	131.0	174.0	218	262	348	436	524	610	696	784	872	1,310	1,740
30:00	8.83	44.2	88.3	133.0	177.0	221	266	354	442	532	620	708	796	883	1,330	1,770
40:00	9.00	45.0	90.0	135.0	180.0	225	270	360	450	540	630	720	810	900	1,350	1,800
48:00	9.07	45.4	90.7	136.0	181.0	227	272	362	454	544	634	724	816	907	1,360	1,810
60:00	9.17	45.9	91.7	138.0	183.0	229	276	366	459	552	642	732	825	917	1,380	1,830
72:00	9.25	46.3	92.5	139.0	185.0	231	278	370	463	556	648	740	883	925	1,390	1,850
100:00	9.37	46.9	93.7	141.0	187.0	234	282	374	469	564	656	748	843	937	1,410	1,870
500:00	9.83	49.2	98.3	148.0	189.0	246	296	378	492	592	674	756	870	983	1,480	1,890
1,000:00	10.00	50.0	100.0	150.0	200.0	250	300	400	500	600	700	800	900	1,000	1,500	2,000
∞	11.35	57.0	114.0	171.0	228.0	285	342	456	570	684	798	912	1,036	1,140	1,710	2,280

INSTRUCTIONS AND SAMPLE CALCULATIONS FOR TABLE A-4

Column 1 gives the time after the burst in hours and minutes. The headings at the top of the other columns are the dose rates at 1 hour after the burst. The entries in the body of the table give the total accumulated dose from the instant of the explosion up to the given time. Proper use of Table A-4 is best illustrated by sample problems.

PROBLEM: What dose has been accumulated by a person who has been present at a given point since the bomb went off 2-1/2 hours earlier? The Dose Rate at 1 hour after the burst was 25 r/hr.
SOLUTION: Refer to column headed 25. Entries give total accumulated dose at given times: At 8 minutes, 98 roentgens; at 30 minutes, 140 roentgens; and at 2 hours, 180 roentgens.

PROBLEM: What dose would be received by a person who came to this given point 2-1/2 hours after the burst and stayed until 10 hours after the burst?
SOLUTION: This would be merely the difference between the dose at 10 hours and at 2-1/2 hours, or (referring to column 25) 205 r - 180 r = 25 r.

TABLE A-5

ACTIVITY-MASS RELATIONSHIP - SPECIFIC ACTIVITY				
ISOTOPE	HALF-LIFE	(unit)	CURIES/GRAM	GRAM/CURIE
H-3	12.46	years	9.60×10^{3}	1.04×10^{-4}
C-14	5568	years	4.61	0.22
N-16	7.35	secs.	9.6×10^{10}	1.04×10^{-11}
Na-24	15.06	hours	8.69×10^{6}	1.15×10^{-7}
P-32	14.3	days	2.85×10^{5}	3.5×10^{-6}
S-35	87.1	days	4.28×10^{4}	2.34×10^{-5}
Cl-36	4.4×10^{5}	years	2.27×10^{-2}	44.1
A-41	109	min.	4.22×10^{7}	2.37×10^{-8}
K-42	12.44	hours	6.01×10^{6}	1.66×10^{-7}
Ca-45	152	days	1.91×10^{4}	5.23×10^{-5}
Cr-51	27.8	days	9.23×10^{4}	1.08×10^{-5}
Fe-55	2.94	years	2.22×10^{-3}	4.50×10^{-4}
Mn-56	2.576	hours	2.18×10^{7}	4.59×10^{-8}
Ni-59	8×10^{4}	years	7.61×10^{-2}	13.1
Fe-59	45.1	days	4.92×10^{4}	2.03×10^{-5}
Co-60	5.27	years	1.14×10^{3}	8.81×10^{-4}
Cu-64	12.8	hours	3.83×10^{6}	2.61×10^{-7}
Zr-65	250	days	8.05×10^{3}	1.24×10^{-4}
Ga-72	14.3	hours	3.04×10^{6}	3.29×10^{-7}
As-76	26.8	hours	1.54×10^{6}	6.48×10^{-7}
Br-82	35.87	hours	1.07×10^{6}	9.37×10^{-7}
Rb-86	19.5	days	7.80×10^{4}	1.28×10^{-5}
Sr-89	53	days	2.77×10^{4}	3.61×10^{-5}
Sr-90	19.9	years	2.00×10^{2}	4.99×10^{-3}

$$\text{SPECIFIC ACTIVITY (curies/gram)} = \frac{1.308 \times 10^{8}}{T_{1/2}\ \text{(days)} \times \text{atomic weight}}$$

TABLE A-5 (continued)

ISOTOPE	HALF-LIFE	(unit)	CURIES/GRAM	GRAM/CURIE
Y-90	61	hours	5.72×10^{5}	1.75×10^{-6}
Y-91	61	days	2.36×10^{4}	4.24×10^{-5}
Mo-99	67	hours	4.73×10^{5}	2.11×10^{-6}
Ru-106	1.0	years	3.39×10^{3}	2.95×10^{-4}
I-131	8.14	days	1.23×10^{5}	8.15×10^{-6}
Cs-134	2.3	years	1.16×10^{3}	8.62×10^{-4}
Cs-137	33	years	79.4	1.26×10^{-2}
La-140	40	hours	5.61×10^{5}	1.78×10^{-6}
Ba-140	12.8	days	7.30×10^{4}	1.37×10^{-5}
Pr-144	17.5	min.	7.48×10^{7}	1.34×10^{-8}
Ce-144	282	days	3.22×10^{3}	3.10×10^{-4}
Pm-147	2.6	years	9.39×10^{2}	1.07×10^{-3}
Ta-182	111	days	6.47×10^{3}	1.54×10^{-4}
W-185	73.2	days	9.66×10^{3}	1.04×10^{-4}
Au-198	2.7	days	2.44×10^{5}	4.1×10^{-6}
Au-199	3.15	days	2.09×10^{5}	4.79×10^{-6}
Tl-204	3.5	years	5.03×10^{2}	1.99×10^{-3}
Po-210	138.3	days	4.5×10^{3}	2.22×10^{-4}
Po-212	3×10^{-7}	sec.	1.8×10^{17}	5.6×10^{-18}
Ra-226	1622	years	0.98 or 1	1.02
Th-232	1.39×10^{10}	years	1.11×10^{-7}	$9. \times 10^{6}$
U-233	1.62×10^{5}	years	9.51×10^{-3}	1.05×10^{2}
Th-234	24.1	days	2.32×10^{-4}	4.31×10^{-5}
U-235	7.13×10^{8}	years	2.14×10^{-6}	4.67×10^{5}
U-238	4.49×10^{9}	years	3.36×10^{-7}	2.98×10^{6}
Pu-239	2.436×10^{4}	years	6.17×10^{-2}	16.2

TABLE A-6
APPLIED PHYSIOLOGY

1-Water Balance:

DAILY WATER INTAKE

Water of Oxidation	0.3 liters
In foods	0.7 liters
As fluids	1.5 liters
Total	2.5 liters

DAILY WATER OUTPUT

Sweat	0.5 liters
From lungs	0.4 liters
In feces	0.1 liters
Urine	1.5 liters
Total	2.5 liters

(The total water content of the body is 50 liters)

2-Respiration:

AREA OF RESPIRATORY TRACT

Respiratory interchange area	50 m^2
Nonrespiratory area (upper tract and trachea to bronchiles)	20 m^2
Total	70 m^2

RESPIRATORY EXCHANGE

Physical activity	Hours per day	Tidal air (liters)	Respiration per minute	Volume per 8 hours, m^3	Volume per Day, m^3
At work	8	1.0	20	10	20
Not at work	16	0.5	20	5	20

TABLE A-6 (continued)

3- Retention of particulate matter in the respiratory tract:

Retention of particulate matter in the lungs depends on many factors, such as the size, shape and density of the particles, the chemical form and whether or not the person is a mouth breather; however, when specific data are lacking it is assumed the distribution is as follows:

Distribution	Readily soluble compounds (%)	Other compounds (%)
Exhaled	25	25
Deposited in upper respiratory passages and subsequently swallowed	50	50
Deposited in the lungs (lower respiratory passages)	25 (this is taken up in body)	25*

* Of this, half is eliminated from the lungs and swallowed in the first 24 hours making a total of 62½% swallowed. The remaining 12½% is retained in the lungs with a half-life of 120 days, it being assumed that this portion is taken up in body fluids.

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140

APPENDIX B

DERIVATION OF MAXIMUM PERMISSIBLE LIMITS FOR FINAL, STANDARD, AND OPERATIONAL CLEARANCE

In addition to cosmic radiation and radiation from the earth's natural radioactive materials, present-day technology has added radiation from machines and man-made radioactive isotopes. Therefore, Maximum Permissible Levels (MPL's) should be defined to guide personnel in establishing criteria for: (a) uncontrolled use, FINAL CLEARANCE; (b) controlled use, STANDARD CLEARANCE; and (c) hazardous radiological situations, OPERATIONAL CLEARANCE. The MPL's derived in this Appendix are based on the maximum permissible doses given in Table 4.1, Vol. II, and 10 CFR 20, January 1957, "Standards for Protection Against Radiation." The Maximum Permissible Concentrations (MPC's) are based on aerosol MPC's and maximum permissible body burdens of the most restrictive radioisotope to represent the limiting case of unidentified radioactive materials. Simplifying assumptions for aerosol resuspension, skin absorption, ingestion, and body retention have been made also. Measurements of small amounts of radioactivity may require control of background radiation much closer than these hygienic MPL's are designed for. Under any circumstances, radioactivity ought to be controlled as closely as practicable.

"The MPL's derived in this Appendix are provided as reference material and may be so used by naval activities in preparing radiological control procedures. However, final approval of such procedures should be obtained from the appropriate authority. Specifically, Naval Shipyards and Repair Facilities must obtain such approval from the Bureau of Ships. Criteria and procedures for controlling radiation and contamination on board nuclear-powered ships are contained in NAVSHIPS 389-0153, Radiological Controls for Naval Nuclear Propulsion Plants."

A. FINAL CLEARANCE (Suitable for general release to the public; no radiological hazard.)

1. Criteria

The Final Clearance is designed to satisfy the Code of the International Commission and the requirements of the Atomic Energy Commission. It limits: a) the external exposure to 1/10 the industrial maximum permissible dose and b) the concentration in air and water, as well as the body burden, to 1/10 the industrial limit for the most restrictive isotope.

2. Assumptions

For the limitations imposed by aerosol MPC's, the resuspension factor for loose surface contamination is taken to be:

$$4 \times 10^{-8} (\mu c/cm^3) \text{ per } (\mu c/cm^2).$$

For other routes of entry, skin absorption of 1% of the contamination covering 10% of the body surface (0.2 m^2 - this is about the surface area of the hands, face and neck.) For ingestion, 1% of the surface contamination (i.e., that transferred to 20 cm^2 of the hand) is assumed for the transfer cycle from hands to mouth. Intestinal absorption of 25% of all soluble material ingested. Complete retention (100%) of all that is absorbed.

3. MPE's for Final Clearance

a. Gamma dose rate at contact $= \frac{1}{10} \times \frac{5 \text{ r/yr}}{52 \text{ wk/yr} \times 168 \text{ hr/wk}}$

$= 0.05$ mr/hr.

This would be given by 400 d/m per cm^2 of a 1 Mev gamma emitter over a large surface.*

b. Beta dose rate at contact $= \frac{1}{10} \times \frac{10 \text{ rad/yr}}{52 \text{ wk/yr} \times 168 \text{ hr/wk}}$

$= 0.1$ mrad/hr.

This would be given by 35 d/m per cm^2 of a 1 Mev beta emitter over a large surface.*

c. Alpha radiation is not an external radiation hazard.

23. MPC's for Final Clearance

a. Inhalation

The inhalation hazard associated with a contaminated surface may be measured by air sampling or estimated by using a resuspension factor. For very dusty operations (rescue work in bombed brick and mortar debris) in closed spaces, Dunster gives a resuspension factor of 4×10^{-7} $(\mu c/cm^3)$ per $(\mu c/cm^2)$.** For similar work in the open, the factor is 2×10^{-8}.

*Conversion of dose rates to surface activity taken from Figs. A.4 and A.5 of Appendix A of this Volume.
**Dunster, H.J. "The Derivation of Maximum Permissible Levels of Contamination of Surfaces by Radioactive Materials." AERE-HP/R-1495, 5 July 1954.

Ventilation in closed spaces or wind action outdoors will further dilute the aerosol concentration. For the purpose of these calculations, we are assuming a resuspension factor of 4×10^{-8}.

$$S \times r = A$$

$$S = A/r$$

where S is the surface contamination, r the resuspension factor, and A the resulting aerosol concentration. A should be less than the MPC to be met.

(1) Beta-gamma Emitters

Putting in the non-occupational MPC for unidentified β-γ emitters (in the absence of Ac^{227}), i.e., 10^{-12} $\mu c/cc$, we get:

$$S_{\beta-\gamma} = \frac{10^{-12}\ \mu c/cc}{4 \times 10^{-8}\ \frac{\mu c/cc}{\mu c/cm^2}} = 2.5 \times 10^{-5}\ \mu c/cm^2$$

$$= 60\ d/m \text{ per } cm^2.$$

Since 60 d/m per cm^2 of removable beta-gamma activity is required to produce the non-occupational MPC, no aerosol hazard will occur if the surface contamination level of 0.1 mrad/hr (35 d/m per cm^2) is satisfied.

(2) Alpha Emitters

When the alpha contaminant is unidentified we make a similar calculation, using the most restrictive non-occupational MPC, $4 \times 10^{-14}\mu c/cc$.

$$S_{\alpha} = 2\ d/m \text{ per } cm^2.$$

By setting the maximum permissible alpha activity at 2 d/m per cm^2, we need make no qualifications as to the fraction that is removable.

b. Absorption

Under the assumptions named (Para. A.2), the maximum permissible skin contamination is:

$$MPC_{skin} = \frac{1/10 \text{ (permissible body burden)}}{(10\% \text{ body area}) \times (1\% \text{ absorption}) \times (100\% \text{ retention}).}$$

(1) Beta-gamma Emitters

The body burden for Sr^{90}, 2 μc(4.4 x 10^6 d/m), is the most restrictive body burden for beta-gamma emitters. (Radium is considered here as an alpha emitter.) Taking 1/10th of this value for Final Clearance, then:

$$MPC_{skin} = \frac{4.4 \times 10^5 \text{ d/m}}{(2.0 \times 10^3 \text{ cm}^2) \times 10^{-2} \times 1.}$$

$$= 2.2 \times 10^4 \text{ d/m per cm}^2.$$

This is about 1000 times what seems possible, even supposing that a contaminated surface might transfer nearly its own level of activity to the skin. (Single contact at 35 d/m per cm^2.) (The possibility of multiple transfer is considered under c. Ingestion.)

(2) Alpha Emitters

The body burden for natural thorium, if soluble (0.01μc), is the most restrictive body burden for the alpha emitters, other than uranium. (The uranium body burden of 0.005 μc (15 mg) is based on the chemical toxicity rather than its radioactivity.) Taking 1/10th of this value for Final Clearance, and using the same relationship as for the β-γ skin contamination, we get:

$$MPC_{skin} = 110 \text{ d/m per cm}^2.$$

This is about 50 times what a MPC of alpha contamination, 2 d/m per cm^2 could transfer to the skin at a single contact.

c. Ingestion

Ingestion of radioactive materials usually occurs: a) by the transfer of surface contamination to food products and then to the body, and b) by the transfer of surface contamination to hands, to mouth, into the body. Only the latter is considered here. Under the assumptions named (Para. A.2), the amount absorbed would be:

$$\text{Amount absorbed} = \text{Surface Activity} \times \text{Transfer Factor (1\%)} \times \text{Absorption Factor (25\%)}$$

(1) Beta-Gamma Emitters

If the hands are contaminated to the level producing the MPE for Final Clearance, the total ingested and absorbed is:

$35\ d/m/cm^2 \times 20\ cm^2 \times 0.25 \simeq 200\ d/m.$

This is less than 1/10% of the most-restrictive body burden (4.4×10^5 d/m).

Supposing a person might make multiple transfers from contaminated surface to hands to mouth, let us calculate the area that 1/10 maximum permissible body burden occupies when the surface is contaminated at 35 d/m per cm^2.

$4.4 \times 10^5\ d/m \div 35\ d/m/cm^2 \simeq 10^4\ cm^2\ (10\ ft^2).$

Dividing this area by the fraction that gets from the hands into the mouth and the fraction of this that is absorbed:

$$10\ ft^2 \div \left(\frac{1}{100} \times \frac{1}{4}\right) = 4000\ ft^2.$$

It would appear impossible for a person to wipe and transfer a significant amount of radioactivity from a surface contaminated at 35 d/m per cm^2.

(2) Alpha Emitters

A similar calculation for alpha contamination gives:

$2\ d/m/cm^2 \times 20\ cm^2 \times 0.25 = 10\ d/m.$

This is about 1/2% of the most restrictive body burden (2.2×10^3 d/m). As above, the area to provide a permissible body burden by multiple transfer is:

$2.2 \times 10^3\ d/m \div 2\ d/m/cm^2 \simeq 10^3\ cm^2\ (1\ ft^2)$

$1\ ft^2 \div \left(\frac{1}{100} \times \frac{1}{4}\right) = 400\ ft^2.$

The factor of safety against multiple transfer of surface contamination appears to be only about 1/10 as large for α as for β-γ. It would seem prudent to establish an upper limit to the uncontrolled release of alpha contamination. One-tenth body burden absorbed means 40 body burdens in the environment. In recognition of the uncertainties involved and considering that the important alpha emitters have a long half-life, it is recommended that any single release of contaminated equipment into the environs be limited to 10 body burdens. This limit on the total amount, in combination with the limit of 2 d/m per cm^2, should make the body retention of any significant amount of alpha contamination highly unlikely.

5. Summary of Final Clearance MPL's

Table B.1 is a summary of the Final Clearance MPL's for unidentified radioactive materials in an unrestricted or uncontrolled area. The values are based on not exceeding the limits specified in 10 CFR, Part 20, for persons in uncontrolled areas, a) as to hourly, weekly, and quarterly external exposure and annual dose accumulation, or b) as to body burden.

TABLE B.1

FINAL CLEARANCE MPL'S FOR UNIDENTIFIED RADIOACTIVE MATERIALS TO COMPLY WITH 10 CFR, PART 20

Radiation	Unit of Measurement	Area, Equipment, Personnel and Clothing
Gamma at contact	mr/hr	0.05
Beta at contact	mrad/hr	0.1
Alpha at contact	$d/m/cm^2$	2*
Beta-gamma at contact	mrad/hr	0.1**

*Total amount of radioactive material should not exceed 10 times the body burden for any single release of equipment or clothing.

**Not to include more than 0.05 mr/hr of γ.

The beta and gamma Final Clearance values summarized in Table B.1 represent radiation levels that are the same order of magnitude as background. Certification of Final Clearance for unidentified radioactive materials implies that there is no significant activity above the natural level.

For known alpha emitters, the 2 d/m per cm^2 Final Clearance value may be increased by the ratio of the known emitter's permissible body burden to that of natural thorium (0.01 μc). However, the total amount of alpha emitters released at any one time should not exceed 10 body burdens of the isotope involved. This limitation is recommended to prevent an absorption or ingestion hazard and to minimize the hazard of concentrating the alpha emitters which may occur in some industrial processes such as laundering or smelting. For any single isotope (beta-gamma emitters), if the half-life is known, Final Clearance dose rates can be increased at the time of release, as indicated in Table B.2, without exceeding the dose rate, dose, and body-burden limitations. This Table is based on the accumulated dose from a single isotope given by:

$$\text{Accumulated gamma dose} = \frac{I_o}{\lambda}\left(1 - e^{-\lambda t}\right)$$

with the following limitations: $I_o \leq 2$ mr/hr

dose for continuous exposure:

In 1 week $\leq$ 100 mr

In 1 quarter $\leq$ 120 mr

In 1 year $\leq$ 500 mr

The Final Clearance beta limitations are double the gamma limitations if the beta radiation has a half-value layer of less than 1 mm of soft tissue.

TABLE B.2

BETA AND GAMMA FINAL CLEARANCE AS A FUNCTION OF HALF-LIFE TO COMPLY WITH 10 CFR, PART 20

$T_{1/2}$ (Hours)	Final Clearance Level for Indefinite Half-life may be Multiplied by	Decay Constant λ(Hour^{-1})	Final Clearance Dose Rate at Contact	Accumulated Dose in		
				168 Hr	1 Qtr	1 Yr
Gamma			mr/hr	mr	mr	mr
≤35	40	1.98×10^{-2}	2.0	100	101	101
>35 but ≤80	20	8.34×10^{-3}	1.0	90	120	120
>80 but ≤150	10	4.17×10^{-3}	0.5	65	120	120
>150	1	Decay insignificant	0.05	8	120	500
Beta-gamma			mrad/hr	mrad	mrad	mrad
≤35	40	1.98×10^{-2}	4.0	200	202	202
>35 but ≤80	20	8.34×10^{-3}	2.0	180	240	240
>80 but ≤150	10	4.17×10^{-3}	1.0	130	240	240
>150	1	Decay insignificant	0.1	16	240	1000

If the early higher dose rates can be tolerated, and clearance be based solely on the permissible yearly accumulation (0.5r for γ and 1.0 rad for β), then the shorter-lived-isotopes contamination can be cleared at a somewhat higher level, as shown in Table B.3.

TABLE B.3

FINAL CLEARANCE DOSE RATES BASED ON A YEARLY DOSE OF 0.5R OR 1.0 RAD

$T_{1/2}$ (Hours)	Final Clearance Level for Indefinite Half-life may be Multiplied by	Final Clearance Dose Rate at Contact	
		Gamma (mr/hr)	Beta-gamma (mrad/hr)
≤35	190	9.5	19.0
>35 but ≤80	90	4.5	9.0
>80 but ≤150	40	2.0	4.0
>150 but ≤1.7×10^3	4	0.2	0.4
>1.7×10^3 but ≤4.8×10^3	2	0.1	0.2

B. STANDARD CLEARANCE. (Nominal radiological hazard not too great for ordinary operations in a restricted area.)

1. Criteria

The criteria for Standard Clearance are based on not exceeding any of the following limits: a) one yearly MPE (5r or 10 rad*), b) the most restrictive occupational aerosol MPC, c) the most restrictive maximum permissible body burden, d) an occupancy factor of 40 hr/wk.

2. Assumptions

Same as for Final Clearance (page 142).

3. MPE's for Standard Clearance

a. Gamma

Gamma dose rate at 3 ft above surface = 5r/yr = 0.1r/40 hr wk = 2.5 mr/hr.

This would be given by 35,000 d/m per cm^2 of a 1 Mev γ emitter over a large surface.

*Providing at least half is absorbed in 1 mm of skin.

b. Beta

Beta dose rate at contact = 10 rad/yr = 0.2 rad/40 hr wk = 5 mrad/hr.

This would be given by 2000 d/m per cm^2 of a 1 Mev β emitter over a large surface.

c. Alpha

Alpha radiation is not an external radiation hazard.

4. MPC's for Standard Clearance

The MPC's for Standard Clearance are based on the same assumptions for resuspension, absorption and inhalation used for Final Clearance.

a. Inhalation

(1) Beta-gamma Emitters

The most restrictive occupational MPC for unidentified β-γ emitters, excluding Ac^{227}, is 3×10^{-11} $\mu c/cc$. For the resuspension factor assumed, this would require a surface contamination of 2000 d/m per cm^2. This happens to be the maximum contamination permitted anyhow on account of the MPE for external irradiation. 5 mrad/hr will not produce a β-γ aerosol hazard.

(2) Alpha Emitters

The most restrictive occupational MPC for unidentified alpha emitters is 10^{-12} $\mu c/cc$. Dividing this by the assumed resuspension factor, we arrive at the corresponding surface activity. This turns out to be 60 d/m per cm^2. This then, is the MPC recommended to avoid an aerosol hazard.

b. Absorption

(1) Beta-gamma Emitters

The maximum permissible skin contamination level (on the basis of body burden from absorption) is 10 times that for Final Clearance or

2.2×10^5 d/m per cm^2. However, the limit set by β-γ external exposure (2×10^3 d/m per cm^2, giving 5 mrad/hr above the surface) holds the contamination to less than 1% of this, even if the full activity should be transferred to the skin in a single contact. (The possibility of multiple contacts is considered under c. Ingestion.)

For Standard Clearance, the β-γ contamination must give less than 0.2 rad of external irradiation in a 40 hour week. But any contamination transferred to the skin and not removed, irradiates it 168 hr/wk. The limit for removable contamination should therefore be:

$$\frac{40}{168} \times 2000 \text{ d/m per } cm^2 = 500 \text{ d/m per } cm^2.$$

If the MPC for removable contamination is set at 10 times Final Clearance, i.e., 350 d/m per cm^2, the criterion for continuous exposure to the skin is definitely met.

(2) Alpha Emitters

By similar calculation, the maximum permissible skin contamination is 1200 d/m per cm^2. Since there is no external irradiation hazard, the aerosol problem proves to be the limiting factor. A surface contamination level of 60 d/m per cm^2 (set by the assumed resuspension factor) would allow the skin to be contaminated to about 5% of the MPC for skin absorption.

c. Ingestion

(1) Beta-gamma Emitters

Hands contaminated by 350 d/m per cm^2 of removable β-γ contamination might carry to the mouth as much as is on 20 cm^2 of thumb and finger. If 1/4 of this is swallowed and absorbed, the total is:

$$1/4 \times 20 \text{ } cm^2 \times 350 \text{ d/m/}cm^2 \simeq 2 \times 10^3 \text{ d/m}.$$

It would require more than 2000 such transfers to exceed a permissible body burden (4×10^6 d/m).

Since the number of square meters of contaminated surface might be large and since irradiation from outside and inside the body add together, it is recommended that the stated limit of 350 d/m per cm^2 for removable contamination not be exceeded.

(2) Alpha Emitters

For alpha contamination also, we recommend for Standard Clearance a value 10 times the level for Final Clearance. Calculating as we did for β-γ:

$$1/4 \times 20\ cm^2 \times 10 \times 2\ d/m/cm^2 = 100\ d/m.$$

Even if all removable, over 200 contacts would be required to accumulate a permissible body burden (2.2×10^4 d/m).

(3) Summary of Standard Clearance MPL's

Table B.4 presents a summary of the Standard Clearance MPL's; note that personal clothing and skin contamination are permitted at five times Final Clearance level for β and ten times for α. These are still well below the permissible level of hazard to the personscarrying them. Even though they are carried outside the controlled area, these contaminations are but little removable and the number of persons exposed to them is small. There is, therefore, but little genetic hazard. Work clothing is permitted a somewhat higher β level because of limited hours of exposure. For α, a higher level than 60 d/m per cm^2 would indicate contact with unacceptably contaminated equipment.

TABLE B.4

STANDARD CLEARANCE MPL'S FOR UNIDENTIFIED RADIOACTIVE MATERIALS

Radiation	Unit of Measurement	Area	Equipment	Skin Contamination	Clothing	
					Personal	Work
Gamma at 3 ft above the surface	mr/hr	2.5	2.5			
Beta-gamma at contact	mrad/hr	5**	5**	0.5	0.5	1
Removable beta-gamma	$d/m/cm^2$	350*	350*			
Alpha	$d/m/cm^2$	60	60	20	20	60
Removable alpha	$d/m/cm^2$	20*	20*			

*Total activity removable. Assuming that a wipe takes up to 10% of what is removable, the limit for the activity measured on the wipe for each cm^2 wiped is 35 d/m for β-γ and 2 d/m for α. When 100 cm^2 are wiped, the maximum activity allowable on the wipe is 3500 d/m for β-γ; 200 d/m for α.

**Not to include more than 2.5 mr/hr of γ.

C. OPERATIONAL CLEARANCE (Where radiological hazard requires contamination control and limitation of access.)

Operational Clearance is defined for those radiological situations where necessary work cannot be accomplished within the MPE's and MPC's established for Standard Clearance. The MPL's should be set for each operation according to the necessities. In some cases, they are but little above the MPL's for Standard Clearance. In others, they are higher, but shall not exceed what produces more than the maximum permissible 12r yearly dose, nor the permissible accumulated dose for any person exposed, viz. (N-18) x 5r. (See Table 4.1 of Chapter 4, Vol. II.) The total doses are the limiting measure, without restriction on how rapidly or slowly they may be received (high or low exposure rate). It is not permissible to continue working even at low exposure rates if the MPD is exceeded.

Operational Clearance MPL's for removable contamination set at 10 times above the Standard Clearance MPL's should not present a difficult contamination control problem.

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